SUMMARY

The concrete-faced rockfill dam is a relatively new type of dams with great potential and challenging. It is of practical significance to appropriately understand static and dynamic characteristics of gravelly soils (or corase-grained soils, rockfills) and to establish rational analysis methods for evaluating static and dynamic behavior of concrete-faced rockfill dams (CFRDs) during construction, water filling phase and subjected to earthquake loading. A successful analysis method for predicting dynamic response of earth dams to earthquake is essentially dependent on the incorporation of representative dynamic soil properties in the analyses. In this thesis, bounding-surface constitutive model based on hypoplasticity theory for rockfills is developed and then is incorporated in numerical analyses of concrete-faced rockfill dams based on nonlinear finite element methods.

Firstly, a comprehensive summary of static and dynamic characteristics and related constitutive models of soils is made. It is recognized that the progressive transition from elastic to plastic states, the dependence of the direction of incremental plastic strains on the direction of incremental stresses, stress-induced anisotropy during unloading and reversed loading, as well as dependence of static and dynamic properties should be duly considered in the advanced constitutive models of soils for complex loading conditions. Considering the dependence of failure on confining pressure and dilatancy of coarse-grained soils at high stresses, the hypoplasticity-based bounding surface model for sands proposed by Z. L. Wang is extended to rockfills. By using effective loading index and radial reflection rule to rationally express loading-unloading criteria, the model can simulate different features of coarse-grained soils, which range from simple monotonic loading to complex cyclic loading with different amplitudes and directions. The complex behavior such as dilatancy, inequality of tension and compression strengths, yielding under pure hydrostatic pressure and accumulated plastic deformation during the cyclic loading can be taken into account. Based on experimental results of triaxial tests under constant confining pressure and cyclic tests of rockfill materials, model parameters are determined by using least-squares fitting procedure. The typical values and variation range of the model parameters are given for engineering practice.

Secondly, an adaptive multi-step backward Euler's integration procedure in conjunction with local iterations is employed in numerically implementing of the proposed constitutive bounding-surface model and the subroutine program named as ROCKFILL is coded. The simulation analysis program TSETROCK to predict mechanical behavior of a soil element under the same loading condition as laboratory soil tests is developed. Some model parameters were calibrated through numerical simulation to typical soil tests under special loading paths. Furthermore, numerical simulations are conducted for laboratory tests of rockfill materials with a variety of static loading paths and typical dynamic loading paths

under different consolidation conditions, drainage condition and loading mode. The qualitative correspondence between numerical simulation under variety loading conditions and experimental results demonstrates that the model is applicable for rockfills under varied complex loading paths, the numerical implementation for constitutive model is reliable. Then the model can be employed to predict the static and dynamic deformation and strength characteristics of coarse-grained materials for the complex loading sequences under which the laboratory tests are difficult to perform.

Thirdly, an incrementally-iterative algorithm is developed for three-dimensional finite element methods of nonlinear systems which combines the incremental scheme with iterations. Then it is coupled with the bounding surface constitutive model to the numerical program system CFRDSDB3 for concrete-faced rockfill dams. In order to reproduce the actual characteristics of complex three-dimensional configuration and mechanical behavior of constituent materials, a variety of elements such as solid elements, interface elements are employed respectively for embankment materials, concrete-faced slab, slab-rockfill interface, peripheral joints of slab and toe-slab. At the same time, the dynamic effect of reservoir water is considered based on the modified Westergaard's formulae of additional masses. Moreover, nonlinear static and dynamic analyses of stresses and displacements of concrete-faced rockfill dams during construction and water filling phase as well as seismic response to earthquake are conducted. In addition, the permanent displacements are evaluated based on the proposed procedure. Taking Hongjiadu and Jilintai concrete-faced rockfill dams as examples, the numerical results of nonlinear static and dynamic analyses are obtained. The qualitative correspondence between numerical simulation and existing conclusions and testing results proves again that the bounding-surface hypoplasticity model is capable of capturing essential rockfill behavior under both monotonic and cyclic loading conditions. Furthermore, a comparison between the incrementally-iterative numerical technique and the equivalent linearization approach was carried out. It is shown that the maximum acceleration, the maximum shear strains of the dam body and dynamic stresses of slab are different obviously. Through this comparison, some limitations and drawbacks of the equivalent linear approach cam be well recognized.

Then, the effects of various factors such as combination of multi-directional earthquake loading, various earthquake-induced frequency components and intensity as well as stiffness of slab on static and dynamic response characteristics of CFRDs are systematically investigated on the basis of numerical results. The minor principal stress of slab, the maximum acceleration in up-down stream direction and permanent deformation of the dam body for three-directional earthquake excitation are obviously different from those for unidirectional and two-directional earthquake loading. Therefore three-directional earthquake excitation should be considered in engineering practice if necessary. The seismic response of CFRDs under vibration-type earthquake excitation is heavier larger than that under shock-type earthquake shaking. The peak acceleration, peak shear strain, peak stress of facing slab, displacement of peripheral joints increase with intensity of earthquake. The stiffness of slab has a considerable influence on stresses of facing slab and displacements of peripheral joints. The stress concentration of the slab is not apparent when the modulus of slab is relatively low as in the case of geomembrance-faced rockfill dams.

Besides, conventional static and dynamic analyses respectively based on simple constitutive models are made and new insights for performance of CFRDs are gained. The following two aspects are addressed.

It is found that during reservoir filling, the dam initially behave in much stiffer manner than during construction. Duncan et al (1980) introduced a gradual increase mode in stiffness by using loading functions. However, as in the conventional model, the rockfills will abruptly behaves in a much stiffer mode during the unloading when the stress ratio drops from its peak value. For this unloading phase, an abrupt change of stiffness is employed to replace the gradual change as in conventional Duncan's model. Therefore a reasonable evaluation of stresses and deformations of CFRDs can be achieved. The double-yielding surface model developed by Professor Shen in characterizing inelastic deformation behavior of rockfill materials is also incorporated numerical analyses. The rotation of principal stress axes for certain elements in dam are examined. It has been found that the rotations of the principal stress axes occur even for the elements beneath the axis of the dam. The rotation angle of principal stress axes is about 10^0 during construction phase, increased by 20 percent during reservoir impounding. In addition, by comparing the results of loading paths plotted in $\tau - \sigma_3$ plane and in $p - q$ plane, it can be seen that the relations between effective mean principal stress p and deviatoric stress q can describe actual change of loading paths for both construction and reservoir filling.

A general equation with three parameters used to describe dynamic deformation characteristics of gravel-like coarse materials is proposed by taking on similar numerous forms of the soil-water characteristic curves for unsaturated soil. A nonlinear least-squares computer program is employed to determine optimum values of the parameters for best fitting experimental data presented in the literatures. The equation provides a good fit for soil dynamic behavior over the wide range of shear strain. Mean curves of the ratio $G/G_{\max}$ of dynamic shear modulus and maximum shear moduls varying with shear strain γ for different confining pressure proposed by Rollins et al. can be simulated by varying the value of the parameter a in the general equation. The equation and the equivalent linearization approach together with three-dimensional finite element method were used in dynamic nonlinear analysis of Hongjiadu dam. Based on the abundant numerical computations, some conclusions can be drawn. The confining-pressure dependence of relation curves of shear modulus varying with shear strain on seismic response of CFRD is not considerable. Different combinations of the related dynamic parameters of rockfills have a fair influence on the general characteristics of seismic response of CFRDs including the distribution of peak accelerations of rockfill and dynamic stresses of concrete slab. Some conclusions which are helpful to understand the earthquake-resistant behavior of CFRD are drawn through comparative studies.

Finally, a comprehensive summary for the thesis work is given and some issues for further studies are discussed.