Chapter 7 Summary and Conclusions

7.1 Summary

A new numerical technique for developing and analyzing mechanical properties for porous geomaterials subjected to the high pressures encountered in penetration and blast-type loadings was described in this document. High pressure mechanical properties are required for constitutive models that will numerically simulate the behavior of geologic materials during penetration calculations and during calculations of ground motions due to explosive detonations. The porous materials of interest include wet and dry undisturbed soils, wet and dry rocks, wet and dry soil backfills, and conventional and high-strength concretes and grouts. High pressure mechanical properties can be developed with the aid of the finite element code JAM. JAM is a numerical tool with the capability to: (a) calculate strains, total and effective stresses, and pore fluid pressures for fully- and partially-saturated porous media, (b) calculate the time dependent flow of pore fluids in porous media, (c) model nonlinear irreversible stress-strain behavior, including coupled shear-induced volume change, and (d) simulate the effect of nonlinear pore fluid compressibility and the contribution of the compressibility of the grain solids for stresses up to several hundred megapascals. JAM simulates quasi-static axisymmetric laboratory mechanical property tests, i.e., the laboratory tests are analyzed as boundary value problems. Given a limited amount of drained mechanical property data, JAM can be used to verify laboratory test results or to predict unavailable laboratory test data, e.g., it can be used to predict undrained properties at various levels of saturation.

In this document, the features and algorithms implemented in JAM were described and the code's ability to simulate both the low and high pressure behavior of porous geomaterials was demonstrated. In Chapter 3, the FE model implemented in JAM was described and the equations for the residual forces were developed. The significance of the concept of effective strains in understanding the effective stress environment of porous materials subjected to high pressure loadings under undrained boundary conditions was demonstrated. The incremental tensor $d\varepsilon_{kl}^{g}$, representing the grain compression due to pore fluid pressures, was a key component in determining the effective strains. With this term included in the general stress-strain relation, effective stresses were calculated in a simple and straightforward manner. In addition, the residual force equations were developed for a nonlinear incremental finite element program that employs a modified Newton-Raphson solution scheme. Although numerous papers pertaining to the FE equations governing pore fluid flow in a deforming porous solid were available in the literature, none outlined the equations required to calculate the residual forces.

The equations developed from the Biot theory required expressions for the bulk modulus of the pore fluid and grain solids. To determine the bulk modulus of the pore fluid, the concept of a homogeneous pore fluid was adopted to treat partially-saturated materials. Using this concept, the pore fluid was regarded as a compressible mixture of air and water and based on the equations of state (EOS) for air and water, equations for the bulk modulus of an air-water mixture were developed. In order to calculate the compressibility of the air-water mixture, equations were also developed to calculate the degree of saturation in a deforming porous skeleton. The bulk modulus or compressibility of water was evaluated from the Walker-Sternberg EOS for water. Grain solids were treated as either linear or nonlinear elastic materials or as nonlinear hysteretic materials; each method for calculating the bulk modulus of the grain solids was described in Chapter 3. The hysteresis observed during undrained hydrostatic loading of fully-saturated materials and caused by occluded porosity may be simulated using the nonlinear hysteretic grain compressibility model. The hysteresis in the model simulates the irreversible crushing of the occluded porosity.

In Chapter 4, the features of the cap model and the relevant equations were documented and the steps required to implement the cap model in the FE code were summarized. The elastic-plastic strain-hardening cap model was incorporated into JAM to calculate the time-independent skeletal response of the porous solids. The cap model enables JAM to model nonlinear irreversible stress-strain behavior and shear-induced volume changes. In order to adequately fit the drained Salem limestone mechanical properties, the original eight-parameter cap model was modified to a 14-parameter model. Two material fitting constants were added to each of the two elastic response functions, which govern the behavior of the model in the elastic regime, and to the function R, which determines the ratio of the major to minor axes of the cap. To insure that the cap model was correctly incorporated into the finite element program, several laboratory stress- and strain-path tests were numerically simulated. These calculations were compared with the output from a cap model driver exercised over the same laboratory stress and strain paths. The two programs produced similar results.

In Chapter 5, several problems with plane or axisymmetric geometries were solved with JAM to test and verify that the eight-node quadrilateral element and numerous other algorithms were correctly incorporated in the FE program. The eight-node quadrilateral element was implemented in JAM to calculate both the displacements and pore fluid pressures. This isoparametric element has 16 displacement and four pore-fluid degrees of freedom. Four Gauss integration points are used in each element. For each verification problem, selected output from JAM was compared with closed form or analytic solutions. These problems included one- and two-dimensional consolidation problems, Cryer's problem of a consolidating sphere of soil, and a thick-walled cylinder problem.

Numerical simulations of limestone behavior under drained and undrained boundary conditions were presented in Chapter 6. A 14-parameter cap model fit was developed for the drained skeletal response of limestone. Single-element calculations demonstrated the ability of the FE code to simulate the drained, fully-saturated undrained, and partially-saturated undrained responses of the limestone under several different load and unload boundary conditions. The utility of the FE code was demonstrated by the simulation of drained and undrained triaxial compression tests. These simulations also revealed the influence end-cap restraint had on the stress and strain states in simulated test specimens.

7.2 Conclusions

From the documented research, the following conclusions may be inferred. Adopting an effective-stress mechanics approach in the analysis tool had several benefits. The primary advantage is that the behavior of each constituent in a porous material, i.e., the solids, water, and air, is explicitly treated. Since well developed equations of state are available for the constituents, the predominant uncertainty in modeling a porous material is confined to the skeletal constitutive model. Effective stress mechanics also allow the modeler to have greater confidence in the accuracy of the results, since the complicated interactions of the material phases are treated in a more consistent manner than in a total stress approach.

The concept of effective strains was an essential element in simulating the effective stress environment of porous materials subjected to high pressure loadings under undrained boundary conditions. It dictates that under drained boundary conditions the total and effective strains are equal, therefore the total and effective stresses are equal. Under fully-saturated undrained boundary conditions the total and effective strains are not equal and the effective stresses are a function of the effective strains, not the total strains.

A simple 8-parameter cap model was incapable of adequately simulating the drained mechanical response of Salem limestone. Thus, a 14-parameter cap model was developed to include three-term nonlinear functions for the elastic bulk and shear moduli and the function R (the ratio of the major to minor axes of the elliptical cap). This latter function was critical in adequately representing the limestone's drained uniaxial-strain stress-path response. Having fit the cap model to the recommended drained limestone properties, JAM predicted the recommended fully-saturated undrained limestone behavior with a high degree of accuracy. The three key components to obtaining this accuracy were the drained skeletal constitutive model (the limestone cap model fit), the EOS for the pore water, and the model for the grain solids. Since the code adequately predicted the undrained response of fully-saturated limestone, it was used to predict the undrained response of partially-saturated limestone under several different boundary conditions.

As the stress levels of interest in this research were much greater than the pore-air surface tension stresses, the concept of a homogeneous pore fluid (HPF) worked very well. In using this concept, one assumes that a three-phase material containing air, water, and solids may be replaced with a two-phase material containing a compressible pore fluid and solids. A partially-saturated material is transformed into a fully-saturated material with an HPF. Effective stress is calculated in the same manner as for a fully-saturated material and the modulus of the pore fluid is calculated based on the modulus or compressibility of an air-water mixture.

The FE program JAM eliminates a deficiency in the process of developing and analyzing mechanical properties for porous geomaterials by furnishing an advanced analysis tool to the engineer who is providing properties to material modelers or ground shock calculators. The FE program's ability to supplement laboratory test results is directly applicable to both mechanical property development and numerical computational efforts.