Chapter 1 Introduction

1.1 Background

The analysis of earth and earth-structure systems subjected to intense transient (blast-type) loadings is typically the responsibility of researchers in the general fields of engineering, soil, and rock mechanics. A key aspect in the successful analysis of these systems is understanding the "high pressure" behavior of geomaterials. Much of the research in the general area of high pressure behavior of geomaterials has been promoted by two research communities, the defense community and the geotechnical community involved in large dam construction. A large quantity of research related to underground nuclear testing and nuclear weapon effects was performed during the "cold war" for the Department of Defense (DoD) and the Department of Energy (DOE). Stress levels of interest during underground nuclear tests vary from megabars (1 megabar = 10^5 MPa) to ambient in-situ stresses. High pressure material property tests must be conducted over these wide stress ranges in order to develop constitutive models that will numerically simulate the behavior of the emplacement media. With the termination of all underground nuclear testing, numerical simulations are the only means available to DoD and DOE researchers to study the effects of these weapons.

The conclusion of the cold war has not eliminated the need for high pressure material research. Military construction and weapon designers must be able to assess the vulnerability of underground structures to conventional weapons and the lethality of conventional munitions. Figure 1.1 illustrates typical attack scenarios for a buried protective structure. It is cost prohibitive to field test prototype structures of this type in the various geologic materials of interest to designers. Therefore, high pressure material properties are required for constitutive models that will numerically simulate the behavior of geologic materials during the penetration simulation and during the calculation of ground motions due to the explosive detonations. The porous materials in Figure 1.1 include wet and dry undisturbed soils, wet and dry rocks, wet and dry backfill, and concrete. Typical stress ranges of interest for the ground shock aspects of this problem are illustrated in Figure 1.2. This figure depicts peak stress attenuation versus range for a fully-buried charge of 454 kg of TNT detonated in three different backfills, a dry sand, a wet clay, and a wet gravelly clay under 1-D spherical boundary conditions. At a distance of 1 meter from the center of gravity of the explosive, the peak stresses range from approximately 400 to 1000 MPa. These stresses attenuate rapidly and at ranges of 10 meters or greater the stress levels are less than 1 MPa. An obvious concern is the ability of the constitutive models used in numerical simulations of these events to capture the fundamental behavior of a variety of porous materials over a wide range of stress levels.

A rigorous analysis of these shock-loaded systems is typically conducted in three different phases. First, laboratory tests are conducted on the geologic materials of interest in order to develop a database of composition and mechanical properties; then, based upon this database, a set of recommended material properties is developed for the constitutive modelers. In the second phase, the modelers fit one or more constitutive models to the recommended material properties. Last, finite element (FE) or finite difference codes are used by calculators to analyze the responses of these systems. Sometimes, little geotechnical data are available when numerical analyses of foreign sites are required. This puts a much greater burden on the geotechnical engineer who is asked to characterize the mechanical properties of the geomaterials at the foreign site.

In performing a complex investigation, an engineer may test and characterize many types of materials. These geomaterials generally fall into the following groups: moist and fully saturated cohesionless soils, desert alluviums, natural and remolded cohesive soils, clay shales, soil and rock "matching" grouts, concrete, and intact and/or fractured rocks. As basing and attack scenarios of DoD analysts become more elaborate, and as the analysis techniques of constitutive modelers and calculators become more refined, greater demands are placed on the engineer who is asked to perform and analyze the laboratory mechanical property tests in order to provide recommended material properties. Modelers and calculators are now requesting total-stress mechanical property data to stress levels of several kilobars (1 kilobar = 100 MPa). Complicated stress- and strain-path tests are frequently included in their lists of desired material response tests. Greater emphasis in effective-stress material properties is now evident in the ground shock community.

Due to the unconventional nature of many of the requested tests, the engineer performing and analyzing the laboratory tests may be uncertain about existing laboratory equipment, e.g., whether it restricts the types of tests that can be conducted. The engineer may question the measured laboratory responses; are they theoretically realistic? An engineer may have specific questions such as: (a) what effect will small amounts of air-filled porosity have on material properties, (b) what loading rates are appropriate for conducting truly drained tests or undrained tests with meaningful pore pressure measurements, and (c) how does one calculate effective stresses at kilobar stress levels for rock-like materials? In some situations, an engineer responsible for recommending material properties may only have low pressure (less than a kilobar) total-stress and effective-stress data from which to extrapolate multikilobar material responses.

An engineer would have a tremendous advantage if a numerical tool were available with which to verify laboratory test results or to predict unavailable laboratory test data. The appropriate numerical tool should give an engineer the capability to calculate both total- and effective-stress material responses. This numerical tool would:

1. calculate strains, total and effective stresses, and pore fluid pressures for fully- and partially-saturated porous media,
2. calculate the time dependent flow of pore fluids in porous media,

3. model nonlinear irreversible stress-strain behavior, including coupled shear-induced volume change, and
4. simulate the effect of nonlinear pore fluid compressibility and the contribution of the compressibility of the grain solids for stresses up to several kilobars.

Since no numerical tool existed to perform these functions, all of the above features were incorporated into a FE code named JAM as part of this research effort. JAM simulates quasi-static, axisymmetric, laboratory mechanical property tests, i.e., the laboratory tests are analyzed as boundary value problems. Features 1 and 2 were incorporated into the code using modified formulations of Biot's coupled theory as advanced by investigators such as Zienkiewicz (1985a) and Lewis and Schrefler (1987). An elastic-plastic strain-hardening cap model calculates the time-independent skeletal responses of the porous solids. This enables the code to model nonlinear irreversible stress-strain behavior and shear-induced volume changes. In order to accurately model the total- and effective-stress responses of multikilobar laboratory tests, fluid and solid compressibilities were incorporated into the code. Following the concept used by Chang and Duncan (1983), partially-saturated materials were simulated with a "homogenized" compressible pore fluid.

This FE program eliminates a deficiency in the process of analyzing and developing mechanical properties for porous geomaterials by furnishing an advanced analysis tool to the engineer 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.

1.2 Purpose and Scope

The purpose of this document is to describe a new numerical technique for analyzing and developing mechanical properties for porous geomaterials subjected to the high pressures encountered in blast-type loadings. The features and algorithms implemented into the FE code

JAM are described and the code's ability to simulate both the low and high pressure behavior of porous geomaterials is demonstrated. This document is organized in the following manner. Chapter 2 provides a brief history of the research conducted to evaluate the behavior of porous materials subjected to static and dynamic high pressure loadings. In Chapter 3, the FE model implemented into JAM is described and the constitutive models available in the code are briefly documented. In addition, the equations of state for air, water, and grain solids are documented, and the equations for compressibility of an air-water mixture are developed. The essential features of the cap model are reviewed and the steps required to implement the cap model into the FE code JAM are summarized in Chapter 4. In Chapter 5, features in the FE program not introduced in earlier chapters are described and solutions from several verification problems are presented as proof that the program works correctly. Numerical simulations of intact limestone behavior under several different drained and undrained boundary conditions are presented in Chapter 6. A summary of the results of this research effort is provided in the final chapter, Chapter 7. Several appendices are included for detailed descriptions of numerical algorithms, simple verification problems, etc. that were not considered appropriate for the main text.

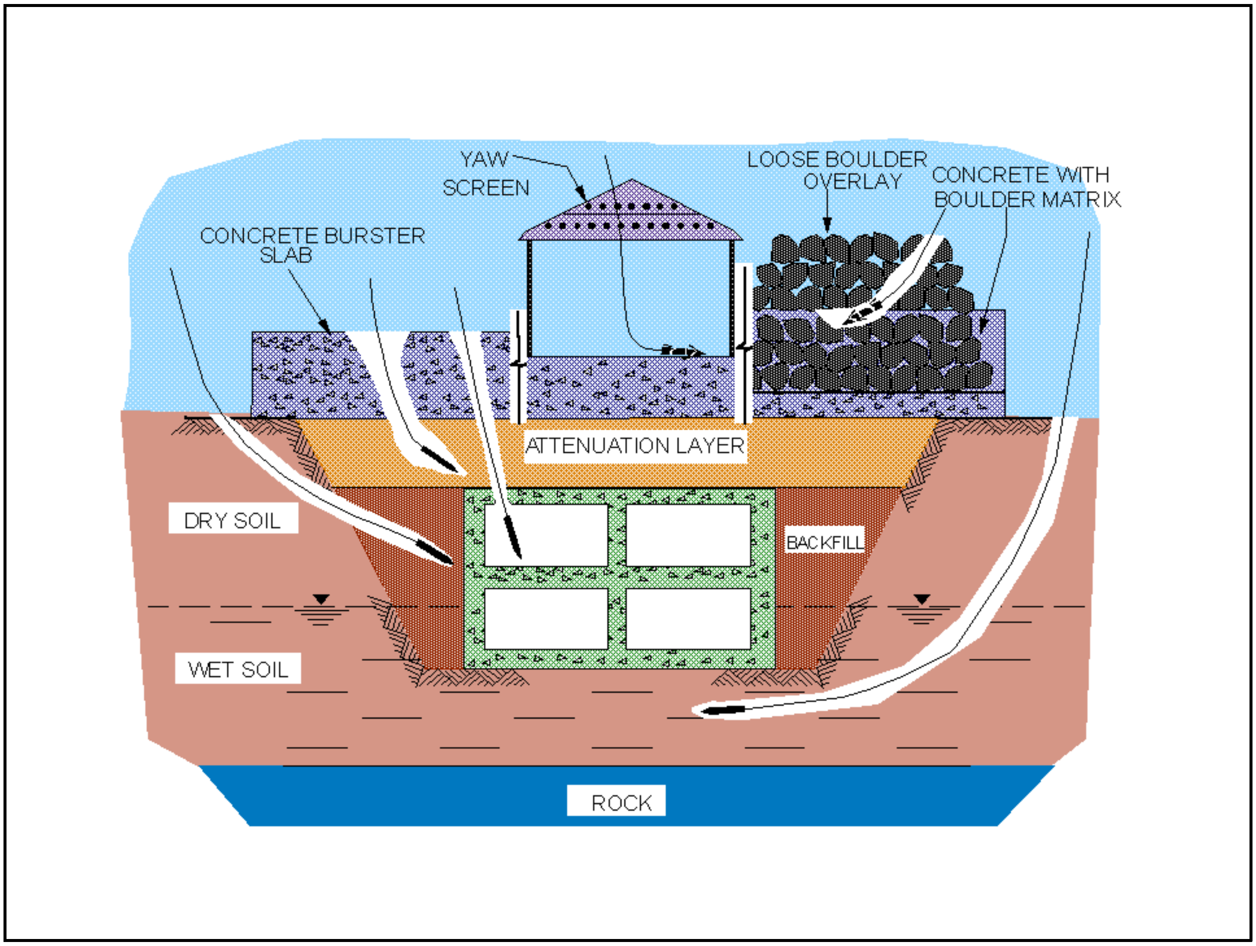

Figure 1.1. Buried protective structure.

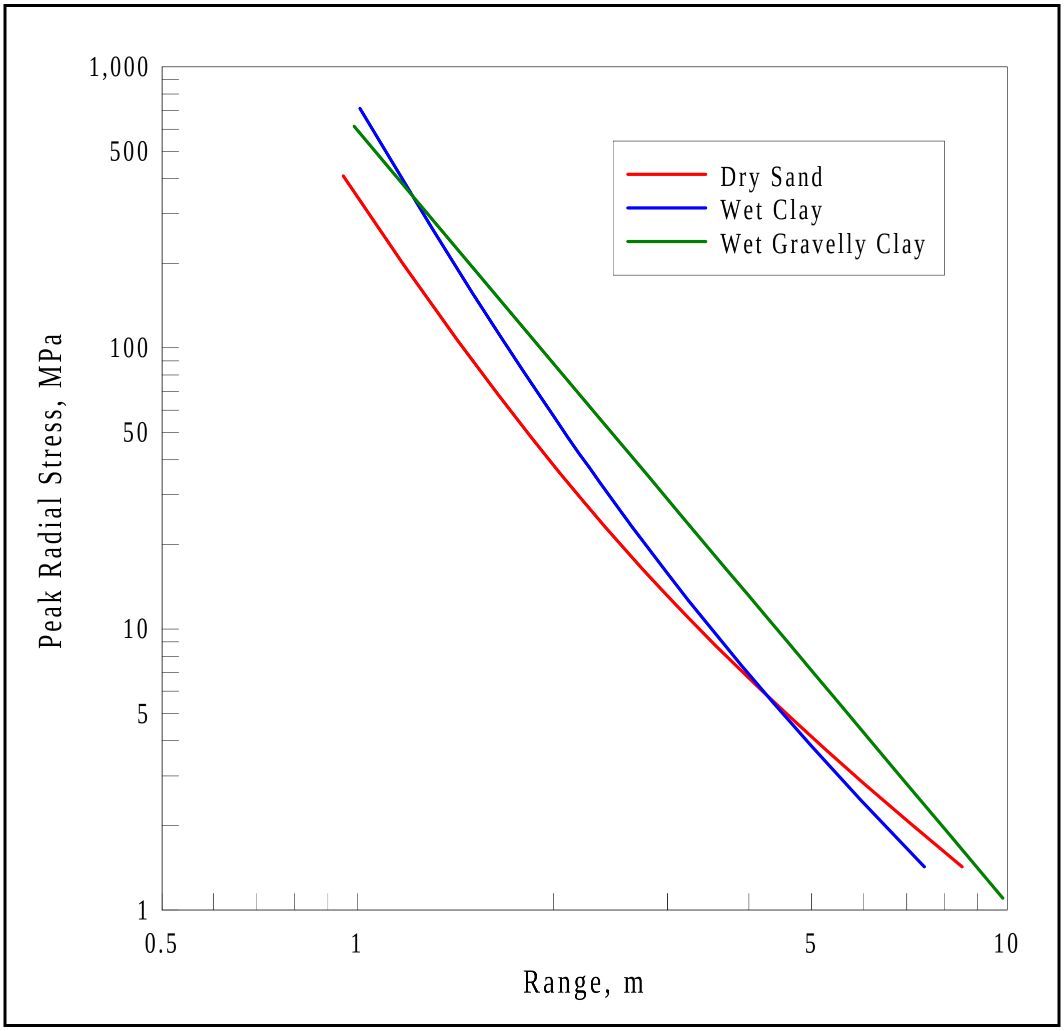

Figure 1.2. Stress attenuation from a 454 kg charge of TNT in three different backfill materials.