Micromechanics of Failure in Granular Geomaterials

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Foreword

The constitutive behavior of materials has for many years been the subject of intense study from a phenomenological viewpoint within the confines of the theory of visco-elasto-plasticity with damage. These theories have proved to be very effective in providing a coherent mathematical framework supporting analytical expressions for constitutive models,whose parameters can be either calibrated from lab experiments, or inferred from inverse analysis or *in situ* tests. Finite element software encapsulating these models represents an important milestone that has led to significant advances in the design of geostructures. For example, traditional engineering concepts such as elastic settlement calculations and plastic limit failure analysis in geotechnics have been unified quite convincingly, and as such can be carried out in a more rational manner under such a powerful modeling paradigm.

However, the above-mentioned approaches, rather than focusing on actual modeling, mostly involve simulations that tend to obfuscate any physical realities of materials, and in particular their micro–meso structure. Yet within the framework of phenomenological constitutive models, this important intrinsic character of the material has resisted omission bias and inevitably reappeared in its simplest form as an "internal length" within the various related formulations. As such, most recent simulations of these phenomenological models advocate the notion of non-locality in the constitutive law, or a high gradient in certain kinematic variables, or the mechanics of a Cosserat medium.

The above efforts have paved the way for a modeling paradigm change that is occurring with the development of micromechanics of granular media. New developments proceed in two complementary directions. In the first, constitutive models are essentially built based at the most elementary level involving a simple local interaction law between grains, such as one governed by an elastic–plastic frictional relationship. The change in scale from the granular level to the macroscopic level and vice versa can be accomplished by way of homogenization/localization techniques. As such, macroscopic constitutive relationships emerge, endowed with information down to the granular scale where the mechanics of contacts are essentially introduced. This modern approach is well illustrated throughout this book with application examples found in most chapters, notably Chapters 2, 3, 4, 5, 6 and 7.

The second development direction relates to applications of the discrete element method to model granular materials. This numerical method, in which the interaction between grains is simulated by either a rigid–plastic or elastic–plastic friction law, belongs to a class of models based on molecular dynamics. These methods are very powerful in the sense that the complexity of natural phenomena is captured principally from the large number of interacting elements rather than from the complexity of local interactions. In this treatise, numerous chapters advocate the discrete element method for analysis, notably Chapters 3, 7 and 9.

Similarly to the title of this book, which has the study of failure as its main theme, a new (at least applied to geomechanics) failure criterion is introduced which is based on bifurcation theory called the second-order work criterion. This criterion allows us to detect the occurrence of diffuse failure modes in the absence of any strain localization, but most importantly identifies the existence of a vast domain of bifurcations before the Mohr–Coulomb plastic limit criterion is reached. The present finding opens up a whole new way of analyzing failure with wide applications to ductile materials in civil engineering, while also keeping in mind that any engineering analysis requires an exhaustive search of failure modes to ensure the safety of structures. This issue is especially addressed in Chapters 1, 2, 3 and 10.

Moreover, the case of failure in brittle geomaterials has evoked great interest in both mathematical developments and engineering applications. This aspect is covered in Chapters 5 and 6.

The constituents that compose a granular assembly can deform considerably and ultimately break, thus drastically changing the macroscopic constitutive behavior of the material. This is covered in Chapters 7 and 8.

Finally, pore fluids have a remarkable influence on the behavior of granular materials such as fine to very fine soils. There have been rapid developments addressing this issue, which is dealt with in Chapters 9 and 10.

In conclusion, this book is largely centered on current scientific issues that are similar to the themes covered in the field of mechanics and engineering of materials. This treatise will certainly become a standard work of reference for its topic.

Félix DARVE

Introduction

The question of materials failure is one of the most fundamental issues faced by engineers. One of the difficulties in analyzing failure within a general framework stems from the diversity of failure modes that can be encountered in practice. In the particular field of geomechanics, we can distinguish two types of failure: a limit state where large displacements subsist at constant loads, and a state at which the geomaterial collapses. For decades now, in both current practice and design, the notion of failure has been addressed within the framework of limit analysis. Moreover, for many years there has been a resurgence of interest in this very question of failure, with the seminal work of Hill in solid mechanics in the 1950s as a point of departure which has been particularized to the field of geomechanics by Darve in the 1980s. As such, failure is viewed as a bifurcation mode that can emerge strictly within the plastic domain, with the notion of instability being introduced to explain the origin of failure in geomaterials. For an engineer involved with gravity-driven natural disasters, the notion of instability is of particular relevance to the slope failure problem, in which a drift from the stability of an equilibrium state leads to large soil movements, and hence a landslide. On the other hand, at a more elementary scale, geomaterials can succumb to instability of a constitutive type due to nonelastic and nonlinear material behavior. The solution of the underlying nonlinear governing equations leads to much richer results that those obtained if the equations were to be linear. Thus the design of geostructures based on elasticity theory may be inadequate because of the nonlinear character of the problem. It is the discrete nature of a geomaterial that makes its behavior highly nonlinear, dissipative and intimately linked to its microstructure. As a result, dissipation at the microscale and the transfer of forces between grains results in material instability that leads to the various modes of failure observed in granular materials.

The objective of this treatise is to gather a number of international contributions on the theme of failure in geomaterials with particular reference to micromechanical aspects. Without pretending to be an exhaustive survey of such a widely debated theme, the book aims to present a glimpse of the current state of scientific knowledge together with the available tools and methods of analysis. The individual contributions have viewpoints that alternate between phenomenological/micro-mechanically enriched and purely micromechanical approaches. Throughout, the authors highlight the various forms of failure that are encountered in geomaterials, while also pointing out the practical implications for the engineer.

The book is organized as follows. The early chapters are dedicated to the analysis of failure as a bifurcation mode. Then failure is treated within the framework of material damage from a micromechanical standpoint. In addition, the effects of particle breakage and large deformations on the response of the material at the specimen scale are examined. Finally, the book ends by looking at the effect of a pore fluid on the failure of the material at the specimen scale, and then moves on to a failure analysis in a boundary value problem setting using computational methods.

The contents and ideas conveyed in each chapter are set out as follows to guide the reader.

Chapter 1 – Controllability of geotechnical tests and their relationship to the instability of soils

Geotechnical lab tests can normally be controlled by either force or displacement, or a combination of both. The question raised in this chapter is whether it is possible to control any loading program before the ultimate state is reached. It is demonstrated that if the stiffness matrix of the system is non-symmetrical (non-associated flow rule), an absolute loss of controllability can be reached before the ultimate state (classical failure condition) is reached. Several examples of homogeneous and heterogeneous bifurcations in element tests are presented, such as the cases of static liquefaction, spontaneous generation of pore pressures, and as the emergence of shear and compaction bands.

The afore-mentioned concepts are then used to analyze the stability of submarine slopes and mud slides. It is also found that within the proposed framework it is possible to justify the validity of commonly used slope stability analysis, where engineers advocate undrained conditions and use a total stress approach.

Chapter 2 – Multi-scale analysis of failure

In many civil engineering applications, such as natural risk prevention in particular, early detection of a failure state is of fundamental importance. Generally speaking, the notion of failure as a bifurcation problem can be defined for a mechanical system as a change in its state with the continuous evolution of certain variables controlling it. The work presented in this chapter is developed within the above framework, and thus comprises three parts.

Firstly, a general framework is set up to describe a certain type of bifurcation for a mechanical system by considering the quantity of kinetic energy it can release. In this approach, the authors discuss various notions such as the loss of sustainability, loss of controllability, or loss of constitutive uniqueness. Finally, using general equations of mechanics in large deformations, the authors establish a criterion for detecting material instability based on the vanishing of the second-order work.

Secondly, the developed theory is used in the specific case of granular materials. In particular, a fundamental relationship is established linking macroscopic second-order work, calculated at the particle assembly level using tensorial quantities, to the sum of microscopic second-order work, computed at the particle contact level using discrete variables.

Thirdly, the above fundamental micro–macro equivalence is used to arrive at a microstructural interpretation of the vanishing of the second-order work (and failure in the broad sense) in a granular assembly. In particular, the authors demonstrate that there are two mechanisms that are at stake: one of a geometrical nature involving the loss of particle contacts, and another of material origin from plastic behavior at contacts.

Chapter 3 – Continuous and discrete modeling of failure in geomaterials

This chapter first illustrates using a very simple example, the application of Hill's stability criterion to describe diffuse failure in granular materials. Then the domain of bifurcation and the cone delimiting all possible unstable stress directions at a given stress state are computed for both dense and loose granular materials from a phenomenological viewpoint based on incrementally nonlinear constitutive relationships. Thereafter, the same results are obtained using the discrete element method. Some examples of diffuse failure triggered numerically by small perturbations using the discrete element method are presented and discussed. Finally, it is shown that essentially the same results as are obtained from phenomenological and discrete element modeling approaches are recovered using a micromechanical model that uses a completely different approach. The latter sheds some light on the mechanism of diffuse failure at the grain scale.

Chapter 4 – Failure analysis using an elastoplastic micromechanical model

The microstructure of granular materials gives rise to macroscopic behavior that is complex and very rich. This chapter describes the microstructural characteristics of material behavior using an elastoplastic micromechanical model.

Firstly, the chapter presents the formulation of the model. The microstructural aspect is embedded in a micro-mechanically derived stress-dilatancy law which thereafter enters as a flow rule into a two-surface elastoplastic model. In addition to internal variables such as density to describe the macroscopic state of the material, a fabric tensor is introduced to represent its microscopic state. The effect of structure on the behavior of sands under drained and undrained conditions following axisymmetric stress and strain paths is discussed based on several examples. In particular, it is shown that for the same initial density, different initial fabrics will give way to different deformational behaviors.

Secondly, the elastoplastic micromechanical model is extended to the cyclic loading regime in order to address the densification of soils in drained conditions and their liquefaction under earthquake loading. The role of fabric on granular material behavior becomes more prominent in the case of small amplitude cyclic loading under drained conditions. Interesting cyclic phenomena such as ratcheting and shakedown conditions are presented.

Chapter 5 – Damage of geomaterials: anisotropy effects and coupling with plasticity

The chapter begins with an introduction to the micromechanics of fractured elastic media. In this framework, the basic concepts and methodology are recalled, then the interactions between fractures and their spatial distribution are addressed. The developments lead to the formulation of unilateral damage models, the importance of which is demonstrated and validated by experimental results.

The case of quasi-brittle geomaterials is considered by coupling frictional damage with dilatancy. In this chapter, the mechanical behavior of granites in multiaxial stress and strain conditions is discussed as an application of the theory.

Finally, microfracturing of geomaterials is addressed in the general framework of plasticity. A macroscopic plasticity criterion for fractured media is considered, which leads to a micromechanical approach with coupled plasticity and damage mechanisms.

Chapter 6 – Continuous damage modeling and discrete approaches to failure

This chapter first briefly recalls some continuous damage models. A quick review of the main homogenization approaches that establish relationships between microfracturing of materials and continuous damage (auto-coherent models, energy equivalence) is then given. The authors show how models based on the physics of disordered media provide credence to the formulation of continuous damage models to analyze failure processes through fuse lattices with the evolution of disorder. Finally, the conceptual shortcomings of continuous models at the local level (softening and localization) as well as the importance of interactions between various defects in the nonlocal approach are highlighted.

Chapter 6 mainly focuses on examples related to concrete and grout materials, and concludes with the issue of scale effects, their practical importance and their use in the identification of models.

Chapter 7 – Effect of particle breakage on the behavior of granular materials

The mechanical behavior of granular materials depends on the fundamental characteristics of particles such as their geometry (shape) and mechanical properties (deformability, strength, and surface topology). This chapter studies the influence of particle breakage on the macroscopic behavior of the medium.

Firstly, Chapter 7 summarizes the main experimental results available in the literature involving particle breakage. On the one hand, experimental data obtained at the particle level helps to establish an empirical relationship between the crushing strength and the mean diameter of the individual particle. Other experimental results pertain to the representative elementary scale such as in a testing specimen. Analysis of these types of test requires the definition of controlling parameters that describe the level of failure in a specimen. These parameters are generally defined based on the evolution of grain size distribution curves before and after the test. Various measures of the level of failure are presented. The mechanical behavior of granular materials are then be analyzed as a function of these parameters defining the level of failure. Experimental results show that the crushing of particles generally occurs at a stress level that does not depend on the size and form of the particles. The mechanical behavior of specimens involving particle breakage is characterized by a decrease in internal friction angle and an increase in compressibility (contractancy) with a concomitant decrease in dilatancy.

Secondly, the chapter describes the incorporation of particle breakage into the modeling of these materials. Two approaches are considered. Continuous methods of analysis basically pertain to damage models. Other methods, of discrete type, are based on the explicit breakage of particles. These discrete models also allow modeling of the time evolution of mechanical characteristics of particles, and hence material aging. The application of these models to rockfill dams in which the breakage of boulders is an essential failure mechanism is presented.

Chapter 8 – Mechanical behavior of granular materials with soft grains

The applicability of Terzaghi's effective stress in soil mechanics to the case of granular materials with soft grains is examined. An analysis based on effective stresses cannot properly account for the differences in friction angles obtained from the drained and undrained compressions of expanded perlite, a material with soft particles. These differences cannot also be attributed to experimental errors arising from the performance and accuracy of testing devices. In fact, grain particles during the test undergo large deformations under high stress levels. As such, the friction angle decreases with rising mean stresses, producing a remarkable friction softening. While expanded perlite is known to be a non-cohesive material, the sample shows an apparent cohesion at low stress levels. The material exhibits structural cohesion arising from flat contacts between the grains under controlled mean stresses. At elevated stresses, the material is pulverized and the internal structure is erased.

Based on the initial suggestion of Taylor and modifications made by Bishop and Skinner to Terzaghi's effective stress principle, a material parameter λ is introduced to correct the effective stresses. A new constitutive law is proposed based on effective granular stresses. The resulting formulation is simple and can be used to describe the mechanical behavior of granular soils with soft grains in triaxial compression in both drained and undrained conditions. The parameter λ, as introduced in the expression of effective granular stresses, is linked to the ratio of grain compressibility to that of the medium. It is recalled that the granular assembly being modeled is composed of soft grains with flat contacts that are subjected to fluid pressures not necessarily equal to the pore pressure fluid in the void.

Chapter 9 – Capillary cohesion of wet granular media

This chapter presents a general study of the mechanical behavior and macroscopic failure of wet granular materials at the scale of the capillary bridge by analyzing their microstructure. The authors describe the physics at the capillary bridge scale, and thereafter derive an analytical expression that relates the capillary force to the volume of the liquid bridge and the distance between two particles of different sizes. The resulting expression are validated through lab experimental tests that involve a pair of grains with a liquid bridge being subjected to a tensile force. The theory is implemented as a discrete element modeling computer program in order to simulate wet granular media. Two case studies are examined in which a granular specimen composed of thousands of grains is subjected to either uniaxial compression or direct shear loading. The numerical results are compared with experimental results obtained for the same loading types. There is close agreement between numerical and experimental results in terms of failure strength (macroscopic cohesion and internal friction).

The above-mentioned tests highlight the influence of water content and its spatial distribution on a granular system as well as its polydisperse character. Both numerical and experimental results is discussed in relation to microstructure and the transmission of forces in a wet granular medium. The authors identify the development of self-stresses arising from an aggregation process that takes place in a wet granular medium during deformation.

Chapter 10 – Numerical modeling of failure mechanisms

In this chapter, the authors present a methodology for modeling failure in granular materials. Firstly, two failure mechanisms are considered: a localized mode and a diffuse mode. The localized mode emerges in the case of dense materials with softening, while the diffuse mode is obtained in the case of loose materials in undrained conditions.

Secondly, the coupling between skeleton deformations and pore pressures is presented in a general framework. Starting from a general model based on mixture theory, progressively more complex models are obtained, such as the 'u-p_w' model developed by Zienkiewicz and co-workers at Swansea.

Thirdly, the behavior of materials such as softening (or liquefaction) of dense sands (or loose) is described within the generalized theory of plasticity. A simple version of the model is presented with an extension to the unsaturated case and collapsible soils.

Fourthly, the numerical modeling aspect is presented, notably the discretization of the mathematical model and the constitutive law via finite elements and the subsequent implementation in the GeHOMAdrid computer program. The model also deals with dynamic problems (e.g. earthquake loading). The authors discuss the solution of numerical problems such as mesh size dependency, mesh locking, and the overestimation of failure load computations.

Finally the chapter illustrates the model by showing examples pertaining to the excavation of a slope and the collapse of a dyke under cyclic loading.

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