# Introduction

After the Second World War, all the developed countries began ambitious infrastructure plans in the domains of transport, energy and water supply. Many large dams, in particular rock-fill dams, were built at that time. The design of such large works was a matter of what we call in France ‘l’Art de l’Ingénieur’, an efficient mixture of science, technology and personal experience. This design was based on classical continuum mechanics. The discrete nature of rock-fill, i.e. the fact that the dam material was an assembly of rock blocks, was usually completely ignored. The dimensions of the constitutive blocks may reach one meter, however; not quite negligible when compared to the dimensions of the whole work.

The important challenge guiding these works in terms of social and economical development was certainly one of the main reasons why a number of engineers and researchers involved in the design, using classical rules, tried to go further by considering the discrete nature of the materials. While the continuum mechanics seemed at that time a well-establisheld field, considering these materials not as a continuum but as they really are (i.e. assemblies of more or less rigid elements contacting each other) was a new and attractive domain of research.

Among the few people who worked on this subject early on, Dantu discovered the strong heterogenity of the distribution of contact forces in granular materials by means of the photoelasticity analysis of 2D analog materials (piles of translucid disks). Biarez, analyzing 2D analog materials (piles of disks), introduced the concept of fabric anisotropy related to the distribution of contact orientation. This was generalized later on by Satake who defined the fabric tensor. In 1966, Weber exhibited a now classical formula relating the local contact forces to a particular Cauchy-like stress tensor. On the basis of particle considerations, Rowe proposed the well-known stress-dilatancy relation which has been extensively used in many phenomenological models in soil mechanics. Horne, Caquot and other researchers tried to relate the classical internal angle of friction used in soil mechanics to the angle of friction measured at the local scale. This isssue is still open today. Marsal, performing triaxial tests at a very large scale with an assembly of blocks, found that the failure of blocks may play an important role in the deformation of the whole assembly.

All these highly innovative results for their time were obtained mainly from tests performed on analog materials equipped with measurement devices; some tests were also performed on actual materials but were more difficult to analyze. Some theoretical attempts relying on idealized particle arrays were also made. At the end of the 1960s, all these attempts reached a dead end due to the lack of mechanical data at the local scale. In 1971, Cundall developed a new approach: the Distinct Element Method (DEM). The method was named in order to highlight the fact that the material is not considered as a continuum, as in the classical Finite Element Method (FEM), but that all grains of the material are considered to be individual rigid bodies interacting through frictional contact laws governed by the dynamical equation. It was also a step towards departing from the quasistatic turn of mind. Some more simple methods in the spirit of Molecular Dynamics were also applied to granular materials. The ideas of J.J. Moreau based on Convex Analysis allowed the proposal of a consistent frame for the non-smooth laws involved in frictional contact, i.e. unilaterality and dry friction. These ideas suggested numerical algorithms known as Non-Smooth Contact Dynamics (NSCD), whereas grains are considered as distinct bodies as they are in the DEM method.

Sophisticated 2D or 3D samples with grains of all shapes with all kinds of interacting laws are implemented today in the numerical software. In the light of discrete numerical simulations and new imaging techniques, the last twenty years of research on granular materials have been marked by an ever-growing interest in the granular microstructure and its link with macroscopic behavior.

The purpose of this book is to provide an overview of some major concepts and analysis tools developed during the last twenty years in the field of granular materials:

– Chapter 1 presents basic definitions and methods to characterize the granular microstructure. Relying on both experimental and numerical data, the distributions of grain velocities and contact forces are analyzed both by their average and in terms of their spatio-temporal fluctuations.

– Chapter 2 states rigorous mechanical concepts allowing the construction of the stress tensor for quite general assemblies of bodies. Numerical examples illustrate the properties of the stress tensor.

– Chapter 3 is concerned with the question of the behavior of granular materials at the scale of a representative sample. Engineers need relevant laws to use in the frame of continuum mechanics (it is impossible to take into account the infinitely numerous degrees of freedom of all grains in a real-size structure). The question of how to deduce the macroscopic behavior of a sample from contact data at the local scale is raised, which belongs to the field of homogenization techniques. This chapter provides methods and concepts to deal with this issue and presents several results.

– Chapter 4 is devoted to numerical simulation methods, mainly the smooth DEM methods and the NSCD methods. The advantages and disadvantages of the different methods are analyzed. Attention is drawn to the fact that a numerical algorithm is in itself a model. Monitoring of numerical simulations must be carried out as in physical experiments and results must be considered shrewdly.

– Chapter 5 will interest mathematically inclined readers. It illustrates the fact that the difficulties met in investigating frictional contact problems have deep mathematical origins.

This book is a completely revised and augmented translation of the former *Micromécanique des matériaux granulaires* by B. Cambou and M. Jean (Hermes Science), 2001.

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