Recent Developments in Distinct Element Methods in the Civil Engineering Graduate Education and Research

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Abstract

In this paper, the recent developments and experiences of the Distinct (or Discrete) Element Method (DEM) in Civil Engineering Education are summarized. The DEM provided an economical approach in many complicated Civil Engineering problems. The author of this paper was among the researchers who applied DEM in civil engineering research; therefore a course in the application of DEM was designed and offered. The course is unique because this is one of the few courses in the nation and DEM is an emerging technology in numerical methods. This course is also innovative due to the extensive faculty-students interaction during the lectures, computer lab work, and student projects. In addition, the DEM application in student research projects has been very successful in the past few years. The DEM was applied in soil compaction, aggregate compaction, and asphalt mixture modeling simulation. The research work at other universities was reviewed and summarized. In order to introduce the advances of the DEM to the graduate curriculum, some materials such as soil, sand, and asphalt mixture materials were introduced to students to better understand the DEM. The DEM simulation approach saved time in experimental testing and improved graduate students' research ability.

Background

The author of this paper applied DEM in research (Buttlar et al. 2004; Buttlar and You 2001; Dai and You 2006; You and Buttlar 2002; You and Buttlar 2004; You and Buttlar 2005; You and Buttlar 2006; You and Dai 2006b) in the past and therefore the author planned a course in graduate student education. The DEM was introduced to students as a numerical analysis method. In the course work, students were taught the application of DEM. The course was offered to graduate students at Texas A&M University – Kingsville (TAMUK) in summers of 2004 and 2005. Due to the increasing demand of the DEM in engineering application and research, it is very critical to have a course on this area. In many universities, it is impossible to find a faculty member in the teaching of this advanced method. There are not many other universities offered the similar course. At University of Pittsburgh, the application of the DEM as a computer aid in a geotechnical program was attempted (Lobo-Guerrrero and Vallejo 2006), where the simulation of a standard laboratory test and different cavities inside a rock mass were introduced to students.

Objective of the Course and Activities

The objective was to teach students numerical analysis methods-focusing on DEM. In order to introduce the advances of the DEM to the graduate curriculum, some materials such as soil, sand, and asphalt mixture materials were introduced to students. Students would also be able to use the image processing software in the advanced material study. In order to help students learn more effectively, a number of research projects have been reviewed including the work by Kolb (Kolb 1984), Magin and Reizes (Magin and Reizes 1990), Mosterman et al. (Mosterman et al. 1994), Penumadu et al.(Penumadu et al. 2000), among others. The class topics include:

Topic 1: introduction
Topic 2: numerical methods in civil/geotechnical engineering
Topic 3: introduction to DEM
Topic 4: geotechnical engineering image processing technique in civil infrastructure (image processing technique for particulate materials)
Topic 5: DEM analysis/simulation and application, including general formulation of DEM, average stress tensor force displacement law, law of motion, boundary and initial conditions, time step, differential density scaling, damping, etc.(Itasca Consulting Group 2004)
Topic 6: contact constitutive models (a stiffness model, a slip model, and a bonding model; and simple viscoelastic model, simple ductile model, displacement-softening model, user-defined contact constitutive models)
Topic 7: advanced implementation issues: cohesive strength adhesive strength, micro-properties
Topic 8: DEM analysis: biaxial and Brazilian test as well as other simulations
Topic 9: particulate materials modeling application
Topic 10: asphalt mixture examples
Topic 11: geotechnical engineering application
Topic 12: students' presentation of numerical methods in civil/geotechnical engineering application (research projects) and final exam

Identification of Concepts in Course Study

In this class, the numerical methods such as calculus and fundamentals, solution of nonlinear equations, interpolation and polynomial approximation, curve fitting, numerical differentiation, numerical integration, solution of differential equations, solution of partial differential equations, eigenvalues and eigenvectors, and numerical optimization were not introduced to students since graduate students should already have the background. In order to provide background information of different numerical methods, finite difference methods (FDM), finite element methods (FEM), boundary element methods (BEM), and

DEM were briefly discussed. Then the DEM was studied in the remainder of the semester.

The DEM is quite a different approach compared to other numerical methods. There are a number of applications of particle physics involving large discontinuous deformations of the particulate media. Some of the examples may include: asphalt concrete and Portland cement concrete manufacturing, aggregate producing, grain transportation, and others. In asphalt mixture, each aggregate is a piece of particulate material and the particulate medium may deform as a solid, flow as a fluid, or behave as individual particles (Itasca Consulting Group 2004). All of these "phases" may play important roles in the analysis, yet at present there is no model available to account for these different characteristics of the particulate material behavior. In order to describe the particulate mechanics problems, a model which simulates the material as a collection of individual particles that interact only at inter-particle contact points are referred as distinct (or discrete) element method (DEM).

Application of DEM in Course Work

Class demonstrations included different packing methods for granular materials and DEM coding as well as the simulations. Students liked to see different packing techniques by programming. The Brazilian test, similar to an indirect tensile test (Ullidtz 2001) in hot mix asphalt was introduced to students to evaluate the compressive and tensile stresses in a specimen as well as the tensile strength of the specimen. Some other DEM simulations such as tip-loaded cantilever beam, collisions with a particle assembly, biaxial test, core flow versus mass flow hopper, dynamics of a beam-column structure, granular flow from a hopper, mine block-caving process, and rockfall (Itasca Consulting Group 2004) were introduced to students using the advanced multi-media facility in the classroom. Students were able to conduct the same simulation in class. Therefore, they were able to repeat the modeling and simulation procedures. Students were also asked to do similar simulations by changing some boundary conditions or other parameters in the codes.

Homework and Research Projects

Students learned by practice. The assignments included different basic modeling concepts. For example, in the DEM, students were asked to conduct a very simple simulation of a two-particle system model (i.e., two elements in series), in which they used a stiffness model, a slip model, and a bonding model, respectively. Simple verification problems were assigned to students to learn the programming technique including particle and geometry generation, contact laws, and displacement and contact force monitoring. Elements may have different shapes of elements such as circular, disk, oval, spherical, or even irregular elements. In this class, only circular elements were used (You and Buttlar 2006; You and Dai 2007).

One of the simple assignments to students was to simulate asphalt mixture compaction. Students needed to generate the boundary geometries (walls) and specific gradation of aggregate particles (a typical coarse aggregate gradation of a type of asphalt mixture). Then a compaction procedure will be applied. Students monitored the contact force generated in the particle-particle contacts. The dark lines indicate the compressive contact force, where the thickness of the line indicates the magnitude of the contact force.

Mini-research projects were assigned to students. The assignments required students use DEM to conduct the following tasks: compaction simulation of sand particles, coarse aggregate sieving simulation, a mix of different soil compaction and some other complicated engineering problems.

Advanced Topics

Advanced topics introduced to students included the most recent modeling technique using DEM (Itasca Consulting Group 2004; You 2003; You and Buttlar 2005; You et al. 2006). For example, cohesive strength and adhesive strength in cohesive material such as asphalt mixture were explained in detail so that students had a better chance to understand the micro-properties of the material. The micro-properties and macro-properties of the material were illustrated to students by using the example from recent research work (You 2003). A clustered DEM approach, or so-called microfabric discrete element modeling (MDEM), was introduced to students to analyze asphalt mixture microstructure. For example, the elements of a piece of asphalt mixture, where various material phases (e.g., aggregates, mastic) were modeled with bonded clusters of elements. Particularly, the DEM was first applied in the asphalt mixture microstructure using a number of elements to represent the aggregate and mastic, where the mastic was assumed to be a combination of asphalt and aggregate finer than 2.36 mm.

Application in Graduate Student Projects: An International Review

Research studies with DEM have appeared in a number of universities. Table 1 shows a list of the authors and institutions which have used DEM in the study of asphalt mixtures. Many researchers have used DEM in this area as well. The author has introduced the application of the DEM in graduate student projects at Texas A&M University – Kingsville (TAMUK) and Michigan Technological University (MTU) (You and Dai 2006a). In Texas, five graduate students completed their master degree research projects using the DEM and finite element modeling simulation. In addition, several student papers have been prepared for publication. Two Ph.D. students and two postdoctoral researchers at MTU are currently conducting further research to develop the DEM in asphalt mixtures so that a friendly user interface and functional predictive tool can be available.

As part of the learning outcome, some students were able to modify the models to conduct an asphalt mixture beam loading study by trimming the specimen to a beam shape and an asphalt pavement permanent deformation study by applying a viscoelastic contact model. Some students were able to use the DEM technique to conduct water contaminant study and sediment study at the TAMUK campus. Using the models developed in the class, students were able to utilize the virtual laboratory simulation

(DEM), by preparing the input parameters measured from the laboratory (Dai and You 2006; You 2003; You and Buttlar 2005). Students were able to compare the lab measurements and the DEM prediction of the mixture complex modulus across a range of test temperatures and loading frequencies. It is found that the students trained in this class were able to understand the basic engineering experiments.

Table 1: An Incomplete International Review of the DEM Study in Pavement Area

Author(s)	Study	Institutions
Rothenburg, L. Bogobowicz, A Hass, R. (Rothenburg et al. 1992)	Micromechanical Modelling of Asphalt Concrete in Connection with Pavement Rutting Problems	University of Waterloo, Canada
Chang and Meegoda (Chang and Meegoda 1997; Chang and Meegoda 1999)	DEM application on asphalt mixture with a modified code	New Jersey Institute of Technology
Buttlar and You (Buttlar and You 2001), You (You 2003)	Development of a Micromechanical Modeling Approach to Predict Asphalt Mixture Stiffness Using Discrete Element Method	University of Illinois-Urbana-Champaign
Abbas and others (Abbas et al. 2005; Abbas 2004)	Simulation of The Micromechanical Behavior of Asphalt Mixtures Using the Discrete Element Method	Washington State University and Texas A&M University
Fu (Fu 2005)	Experimental Quantification and DEM Simulation of Micro-Macro Behaviors of Granular Materials Using X-ray Tomography Imaging	Louisiana State University and Agricultural and Mechanical College
Collop and others (Collop et al. 2004; Collop et al. 2006)	Modelling dilation in an idealised asphalt mixture using discrete element modelling	University of Nottingha, UK
You and Buttlar (You and Buttlar 2002; You and Buttlar 2004; You and Buttlar 2005; You and Buttlar 2006)	Stiffness Prediction of Hot Mixture Asphalt (HMA) Based upon Microfabric Discrete Element Modeling (MDEM)	Michigan Technological University and University of Illinois-Urbana-Champaign
Dai and You (Dai and You 2007)	Prediction of Creep Stiffness of Asphalt Mixture by comparing DEM and FEM	Michigan Technological University

Summary

In this paper, the author presented a Distinct (Discrete) Element Method (DEM) course offered for graduate students. In the course work, students were taught the theory and application of DEM. The course served a variety of functions in the curriculum. First, students learned an advanced numerical analysis technique, which covered basic knowledge in DEM for engineering purposes. The second function was to introduce the students to a wide range of issues common to all disciplines of engineering, including basic engineering problem solving methods, computer operations, computer programming, presentation, and writing reports. The third function of this course was to introduce research concepts such as the micromechanical modeling approach in DEM to students at a high academic level. The course provided students' working knowledge and practical skills in DEM theory and application, with a specific focus on aggregate-asphalt mixture simulation and analysis. Students learned to use DEM in engineering analysis and simulation. This course offered students a very solid background in basic concepts and interesting research topics.

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Biography

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