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Modelling of deformable structures in the general framework of the discrete element method

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A B S T R A C T

The discrete element method (DEM) is particularly suited for the numerical simulation of granular soils interacting with various types of deformable structures and inclusions. Numerous studies have been dedicated to the accurate modelling of particle shape, yet there is a lack of a general framework for modelling deformable structures of arbitrary shapes such as textiles, grids, membranes, tubes and containers. This paper presents a novel generalised approach to this problem in three dimensions. Minkowski sums of polytopes and spheres are used to describe the topology via three simple primitives: spheres, cylinders and thick facets. The cylinders and facets are deformable and can be connected to form grids and other membrane-like structures. A conventional elastic–plastic contact model is adapted to reflect all possible interactions. The implementation is verified by considering spheres moving along a complex membrane structure and a buckling tube. In addition, simulated pull-out tests on a grid and a membrane and bouncing tests of a hollow deformable sphere are reported. The versatility and capabilities of the approach and the potential applications to soil–inclusion problems are demonstrated.

1. Introduction

The discrete element method (DEM) has been used for decades for simulating granular geomaterials ranging from silt to gravel. The method is particularly well suited for simulating soil–geotextile systems due to its robustness when contacts are being created or deleted in multibody systems and when large displacements result from sliding at the interface between different materials or different objects.

In many cases, the solid elements are discretised in the form of spherical elements (or discs in 2D models). However, this simplification is known to bias the mechanical response compared to more realistic (i.e. angular) particle shapes. Solving this issue motivated a number of extensions of the method towards more complex shapes. The possible strategies include rigid clusters of simple elements representing a more complex geometry (Thomas and Bray, 1999; Chareyre and Villard, 2005), polyhedra (Cundall, 1988), sphero-polyhedra (Pournin and Liebling, 2005; Alonso-Marroquín, 2008; Galindo-Torres et al., 2009), Fourrier descriptors of the particle shape (Bowman et al., 2001; Mollon and Zhao, 2013), and the so-called potential particles (Houlsby, 2009).

All these techniques are only valid as long as the mechanical interactions between solid objects are such that their shape remains very close to the undeformed reference state. In other words, a common underlying assumption is that the compliance of contacts is due to a local deformation of the solids near the contact regions, with no significant change of the shapes overall. This assumption does not hold in all cases. Namely, composite systems with soft particles or flexible structural elements incorporated in or interacting with a granular bulk may need to allow large deformations of some of the elements. Examples of such problems are fibre reinforced soils or reinforced concrete, soil–geotextile or soil–geomembrane structures, soils interacting with tyres or inflatable structures.

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None of the aforementioned techniques enables to account for the deformability of the elements directly. Clusters are the only exception, since a rigid cluster of spheres can be turned into a deformable object by allowing internal degrees of freedom, such that the spheres the cluster is made of can move relative to each another. This strategy has been used for simulating fibre reinforcement of soils (Lobo-Guerrero and Vallejo, 2010), geogrid reinforced ballast (Chen et al., 2012), concrete rebars (Shiu et al., 2009) and membranes (Bardet and Proubet, 1991) as flexible networks of spheres. A downside of this approach, however, is that it introduces an artificial numerical roughness at the interface between an object and the surrounding granular material which can cause unrealistic artefacts (Chareyre and Villard, 2005). Therefore, the use of clusters consisting of spherical particles introduces some limitations.

An alternative approach consists of coupling different numerical methods. Most commonly the DEM is coupled to the finite element method (FEM). Thereby, the structural elements are modelled as continuous solids and discretised with finite elements (Villard et al., 2009; Tran et al., 2013). The general framework for such multi-domain coupling between the DEM and FEM is well established (Oñate and Rojek, 2004) and also available with open-source codes (Stránský, 2013). The approach uses each method for what it does best: FEM for the continuum and DEM for the discrete domain. A difficulty, however, is the accurate definition of contact behaviour between the discrete elements and the finite elements for complex three-dimensional objects. In addition, if the FEM domain is composed of volume elements, the number of degrees of freedom of the FEM part can be very large, hence implying high computational costs.

In this work, a general method for modelling deformable objects of arbitrary shape in the framework of the DEM is developed. The method is an extension of the work by Bourrier et al. (2013). It applies directly, yet not only, to grids and membranes. Like others (Pournin and Liebling, 2005; Alonso-Marroquín, 2008; Galindo-Torres et al., 2009), the approach consists in employing Minkowski sums of polytopes and spheres to describe the topology of the objects. Along this line, every shape is represented by a collection of simple primitives: spheres, cylinders, and thick facets. The main difference compared to the previous works lies in the fact that cylinders and facets are deformable. Also, less emphasis is put on the contact detection itself (i.e. deciding if two objects are in contact or not), which is rather straightforward given the simple primitives. Instead the focus lies on the consistent integration of the contact forces for arbitrary movements of the objects, including possible sliding of the contact point along the outer surface and across many primitives. This latter aspect is critical for modelling frictional or cohesive–frictional interactions between objects, though overlooked in many cases by previous authors.

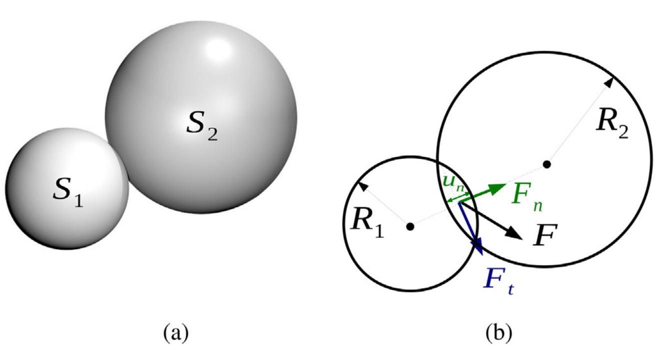

Fig. 1. (a) Sphere–sphere interaction and (b) concept of overlap and contact forces between two spheres.

In Section 2, the basic concept of the DEM is introduced and the general formulation for a contact between two spheres is presented. Section 3 describes all details about the new method for modelling deformable objects of arbitrary shape. The concept of deformable cylinder elements is introduced first, followed by grids and thick facets (PFacets). An explanation how contact points are tracked and how to ensure continuity of the contact forces for every possible movement follows next. The section concludes with some remarks on the time integration. Finally, two complex validation examples (Section 4) and two possible applications (Section 5) of the newly developed model are presented.

2. Discrete element modelling

2.1. Overview

The Discrete Element Method (DEM) consists in modelling bodies as assemblies of rigid locally deformable particles which can interact by contact forces (Cundall and Strack, 1979). The interaction between each particle is considered explicitly and is generally defined via a contact law. The DEM allows finite displacements and finite rotations of discrete bodies of arbitrary shape, which can be approximated by an assembly of bonded spherical particles, to be considered (Donzé et al., 2009). The motion of the particles is governed by Newton's second law and the rigid body dynamic equations are solved by applying an explicit time stepping algorithm. New contacts are automatically updated during the calculation process and the corresponding contact forces are applied. During the explicit interaction, particles are allowed to slightly overlap and in general the contact forces are defined as a function of these overlaps.

The method was implemented into the open-source framework YADE (Šmilauer et al., 2010) and applied to simulate various element types and behaviours, such as plant roots (Bourrier et al., 2013) and wire meshes (Thoeni et al., 2013) to name a few. YADE is a three-dimensional DEM code based on the classical formulation of Cundall and Strack (1979). Being open-source it allows users to study, change and improve the code for their own purpose. Hence, new features can easily be implemented. In this research work, new specific discrete elements have been developed in YADE in order to be able to simulate deformable objects of arbitrary shape, such as grids and membranes, in the general framework of the DEM. In particular, the work by Bourrier et al. (2013) has been extended for this purpose.

2.2. General formulation

The constitutive model of two spheres in contact is presented herein since it is the basis of all other type of interactions used in this work. The contact model used for the sphere–sphere interaction (Fig. 1) relates the relative displacement (or overlap) and relative rotation to the contact force $\mathbf{F}$ and contact moment $\mathbf{M}$ acting at the contact between two interacting bodies. The normal contact force $\mathbf{F}_n$ and the incremental shear force $\mathrm{d}\mathbf{F}_s$ are defined as:

$$\mathbf{F}_n = k_n \mathbf{u}_n \tag{1}$$

$$\mathrm{d}\mathbf{F}_s = k_s \dot{\mathbf{u}}_s \mathrm{d}t \tag{2}$$

where k_n and k_s are the contact stiffness associated to the normal and shear force, $\mathbf{u}_n$ is the normal distance or overlap between the two spheres, $\dot{\mathbf{u}}_s$ is the relative shear velocity, and $\mathrm{d}t$ is the time step.

Considering two spheres S_1 and S_2 the normal and tangential stiffness of the sphere–sphere contact is calculated as follows: