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A Particle Method for the Simulation of Ground Excavation Processes

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Abstract

The present work introduces a Particle Method for the modeling of ground excavation processes. It is called Particle Finite Element Method (PFEM) and it comes from the Computational Fluid Dynamics (CFD). It is very suitable for treating large material deformations and rapidly changing boundaries. This work presents a new application of the method to solid mechanics.

The method has its fundamentals in the classical non linear finite element analysis. Lagrangian descriptions of motion are used as well as an implicit integration scheme. Remeshing strategies are employed in order to identify the boundary surfaces and as a methodology for contact detection between domains. An interface mesh is created for contact recognition. This interface is used for the contact treatment. With a wear rate function, the excavation and damage caused in the ground is quantified. The loss of material due to excavation and wear shapes the domain boundaries via the remeshing process.

Preliminary results obtained show that the method is as a very suitable tool for the analysis and simulation of excavation problems. The computational cost of the method is cheap compared with other methods.

Keywords: Particle methods (PFEM), contact mechanics, wear and excavation, remeshing processes, damage models

1 THE PFEM FOR CONTINUUM SOLID MECHANICS

The Particle Finite Element Method (PFEM) is based in an Updated Lagrangian formulation for the motion description. The fundamental equations of continuum mechanics arise from conservation laws. The well known equations are: *Equation of mass conservation* (continuity equation), *Equation of conservation of linear momentum*, *Equation of conservation of angular momentum*, *Constitutive equation*. We note that any constitutive model can be used in the context of the PFEM. The behavior of the geomaterials is described using Damage Models. They model the fracture in the continuum medium.

The equations are directly developed in terms of the updated Lagrangian measures of stress and strain in its current configuration. The major dependent variables are the initial density $\rho_0(\mathbf{X},t)$, the displacement $\mathbf{u}(\mathbf{X},t)$, and the Lagrangian measures of stress and strain.

1.1 A Particle Based Method

In the Particle Finite Element Method (PFEM) the continuum is described as a cloud of particles of infinitesimal size. A particle is a material point that has some information associated to it. The particles contain all the properties of the continuum (displacements, velocities, strains, stresses, material properties, internal variables, etc.). That means that they have enough information to reedit the original geometry and to recover the properties of a given continuum domain.

This cloud of particles is the basis of the PFEM. From them a finite element mesh is generated at any time step using a *Delaunay* tessellation [1]. The properties of the particles are transferred to the elements of the mesh for the computation. The transfer scheme is a big deal in the PFEM. The information must be accurately transferred from the domain to single particles and the inverse process. Figure 1 shows the particle scheme.

1.2 Meshing Process and Boundary Detection

In the PFEM, the meshing of the domain is essential for the computation with the finite element method. The analysis is focused in the movement of the particles, but the filling of the continua is required for the boundary recognition and contact detection. By means of the remeshing process and the alpha-shape concept together, the boundary of the different body entities is identified. The α-shape method is a way of finding the boundaries of a set of particles. It determines the size of the elements in

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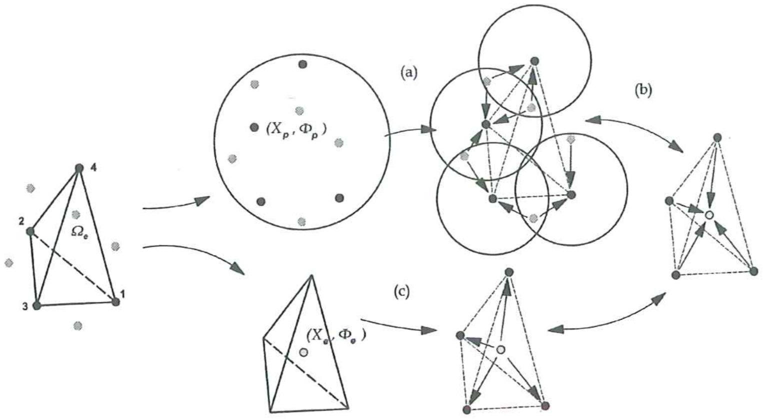

Figure 1: The variables are segregated in elements and particles: (a) Transfer of information from particles to nodes, (b) Transfer from nodes to the element and (c) Transfer from element to nodes. The way back is also performed when the information is updated and recovered

the mesh defined by the point set. With this, the boundary of a solid domain is determined and a mesh is created inside. The particles carry forward enough information to allow the analysis in a new mesh at each time step.

2 TREATMENT OF CONTACT WITH THE PFEM

The PFEM is designed for the treatment of large displacements and large deformations of continuum domains as well as for multi-body systems. The most important physical phenomena that has to be represented is the interaction between multiple bodies. The contact identification is naturally done by the remeshing process and the alpha shape concept.

When the particles of two sub-domains get closer the alpha-shape joint these two sub-domains and creates a larger domain. The detected boundary will contain particles of different bodies. An interface of elements between the two sub-domains is created. These elements are called *contact elements*. The process is displayed in Figure 2(a).

For the PFEM a new formulation for the contact contribution has been developed, it has been named as the *Continuum Constraint Method*. It is based in the interface mesh created in the contact detection. This interface generates large interacting

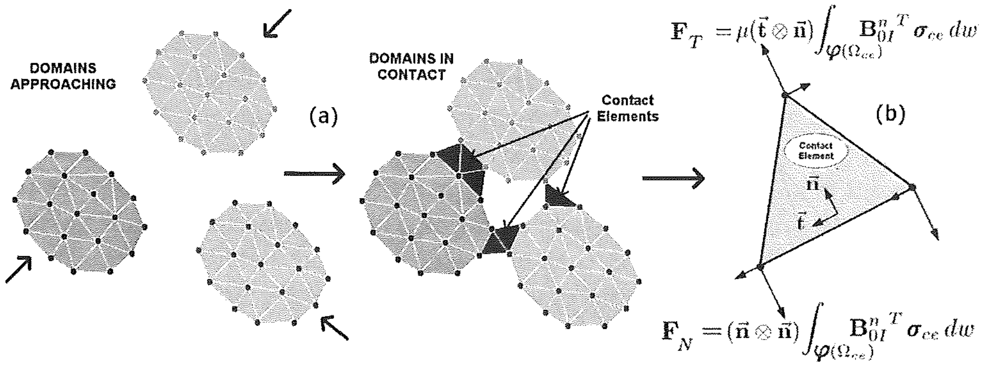

Figure 2: (a) Using the alpha-shapes the detection of contact between sub-domains is done automatically. This generates contact elements when the sub-domains are close enough.
(b) Contact forces in a bi-dimensional contact element

forces due to the interchange of dynamic energy in the contact region. See the contact forces displayed in Figure 2(b).

3 WEAR AND EXCAVATION STRATEGY

Mass loss in a cutting tool and the amount of excavated material that is extracted by the machine is modeled via a wear rate function. It is characterized for each excavating tool and depends on the material parameters. The wear and fracture mechanisms are included in the wear rate function usually described by a linear Archard-type equation [3] as:

$$V_w = K\,\frac{|\mathbf{F}_n|}{H}\,s \tag{1}$$

where V_w is the volume loss of the material along the contact surface, s is the sliding distance, $\mathbf{F}_n$ is the normal force vector to the contact surface, H is the hardness of the material. Constant K is the wear coefficient, which depends on the relative contribution of the body under abrasion, adhesion and wear processes. For the excavation modelling, H and K correspond to a different mechanical and geometrical characterizing properties of the ground and the digging tools.

A volume loss of material is computed by means of the contact forces and the relative sliding distance between particles of different domains. This allows us to shape the ground surface under excavation reducing the tributary volume of the surface particles.

When the volume of worn material associated to a particle and the volume of material are the same, the particle is released. The elements that contain the released particle are eliminated in the next time step. The remeshing process shapes the resultant domain boundaries after computing the loss of material due to excavation and wear.

3.1 Examples

Examples of application of the method to a number of 2D and 3D excavation and rock cutting processes are presented showing the efficiency of the method for this type of problems. Figure 3 shows an example for a Roadheader model. The impacting forces are depicted with the resulting accelerations in the excavation front.

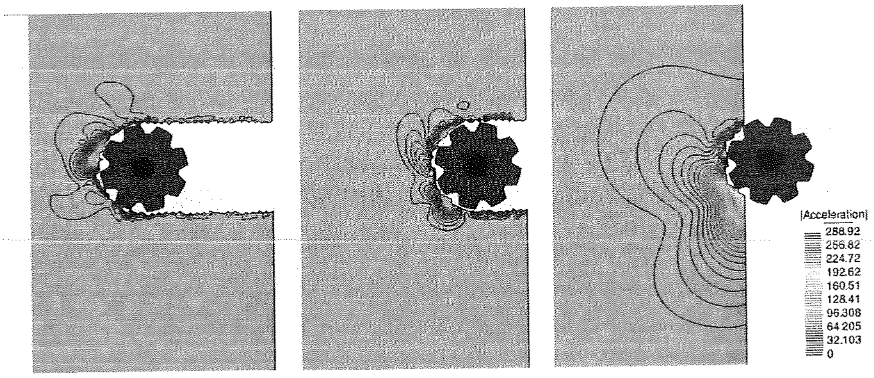

Figure 3: Simulation of an excavation with a roadheader

Figure 4 shows a simulation of an excavation with a TBM. The method allows to compute stresses in the ground and the wave propagation produced by the boring advance. Wear on the rock cutting tools, discs or drag picks, is modeled in a simple and economical way.

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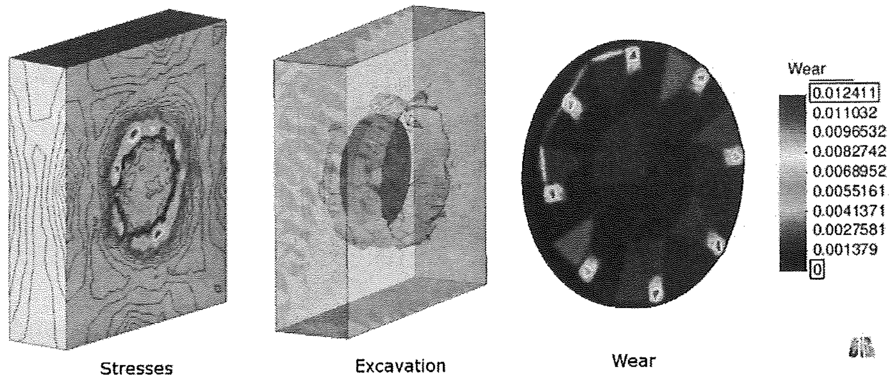

Figure 4: Simulation of an excavation with a TBM

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