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SOIL-MACHINE INTERACTION: SIMULATION AND TESTING

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ABSTRACT

Researchers at Caterpillar have been using Finite Element Analysis or Method (FEA or FEM), Mesh Free Models (MFM) and Discrete Element Models (DEM) extensively to model different earthmoving operations. Multi-body dynamics models using both flexible and rigid body have been used to model the machine dynamics. The proper soil and machine models along with the operator model can be coupled to numerically model an earthmoving operation. The soil – machine interaction phenomenon has been a challenging matter for many researchers. Different approaches, such as FEA, MFM and DEM are available nowadays to model the dynamic soil behavior; each of these approaches has its own limitations and applications. To apply FEA, MFM or DEM for analyzing earthmoving operations the model must reproduce the mechanical behavior of the granular material. In practice this macro level mechanical behavior is not achieved by modeling the exact physics of the microfabric structure but rather by approximating the macrophysics; that is using continuum mechanics or/and micromechanics, which uses length scales, that are larger than the physical grain size. Different numerical approaches developed by Caterpillar Inc. researchers will be presented and discussed.

INTRODUCTION

Geomaterials usually are composed of individual particles that range in size, shape and hardness. Such a structure causes the material to exhibit complex behavior when subjected to machine loading. Building robust virtual machine models is very important for Caterpillar Inc. to be able to understand machine performance and predict structural loads while the machine operates in such

environments. To achieve these goals, the Caterpillar Inc. applied research development team has been developing different techniques to model these phenomena. The reason is essentially to be able to model the different machine operations in different surrounding environments. The different techniques and models are being used to model the soil – machine interaction at different levels of fidelity when the soil is subjected to different loading levels. The level of fidelity is essentially decided by the purpose of the modeling or simulation under consideration. For instance, if the purpose of the analysis is load prediction then the model has to be accurate enough to capture such forces, which mean a high fidelity model is needed. On the other hand, if the purpose is debugging some automation algorithms then a real low fidelity model will do the job. In some cases real-time models are needed; therefore, simplified equations can be used and implemented to run in a real time environment, in this case, force prediction accuracy is not a concern. Finite element method is well developed and mature to be used for soil modeling in application that involve small to large deformation level, where server fragmentation is not experienced. Examples, but not limited to, are tire and track mobility. The lowest fidelity method is the classic soil mechanics or analytic – based approach. Such method is basically dependent on our understanding for fundamentals in soil mechanics and soil dynamics. Then, we try to derive simple equations to describe the force-velocity response for the soil mass while subjected to machine dynamic loads through one or multiple machine implements or tools.

The second approach is the FEM, which is in general, a numerical approximation that represents the solution for systems of partial differential equations. Using FEM to model soil masses usually have several challenges such as; forming the proper equations that represent the real problem while maintaining numerical stability. The different FEM – based techniques developed by Caterpillar Inc. are usually linked to the commercial well-known FEM package, ABAQUS. In such techniques, the material models are in-house developed to suit the material type being dealt with. ABAQUS pre-processor, solver and post-processor are used to handle the problem in hand.

The third approach, which is potentially a higher fidelity approach, is DEM. This method is also called a distinct element method. DEM is the family of numerical methods used to compute the motion of a large number of particles with micro-scale size and above. DEM has been becoming more mature and widely accepted as a robust method to treat engineering problems in granular and discontinuous materials, especially in granular material flows, pharmaceutical applications, rock and powder mechanics. The various branches of the DEM family are the distinct element method proposed by Cundall in 1971 [1], the generalized discrete element method proposed by Hocking, Williams and Mustoe in 1985 [2]. The theoretical basis of the method was established by Sir Isaac Newton in 1697. Williams, Hocking, and Mustoe in 1985 [3] showed that DEM could be viewed as a generalized finite element method. Its application to geomechanics problems is described in the book Numerical Modeling in Rock Mechanics, by Pande, G., Beer, G. and Williams, J.R. [4].

Caterpillar Inc. researchers have been developing and using a DEM code for the last fifteen years; the code is called Rocks3D^{TD}. It uses a very computationally efficient contact detection algorithm and can deal with any particle shape specified by the user. The contact frictional and normal forces are computed using the well-known Hertzian contact model for cohesionless materials. Additional algorithms are implemented to treat cohesive-like bonds when modeling fine-grained materials and rocks. The cohesion is modeled using cohesive pillars that bond neighboring particles together; this pillar can be strained until a strain threshold is reached and then the bond is broken [6]. Recently, Cosserat rotation has been added to the code kinematics along with particle shape indices described by [7]. This additional degree of freedom enabled the code to capture more of the micro-structural properties for the material being modeled (angularity, size, spherecity etc.). While Rocks3D^{TD} is used to model particulate force responses and material flows, it is capable to link to full machine models using in-house built codes for modeling machine dynamics, tire-ground interaction, machine hydraulics, etc.

Rocks3D^{TD} is also capable of interacting with tracked-type tractors to pass proper forces to the machine through the track shoes. The machine tools can be treated as either rigid and/or flexible bodies. The code had been parallelized to take advantage of mutli-threaded processors. It has been benchmarked against other commercial codes; to-date, Rocks3D^{TD} usability, simulation speeds and accuracy have been found more encouraging. As acknowledged by many researchers, it is very challenging to obtain DEM model parameters that best represent real materials, specially, when dealing with fine-grained materials. Rocks3D^{TD} developers have been successful in defining an engineered procedure to map these micro quantities to some material physical and macro quantities. Both small scale laboratory testing and full machine testing are being utilized to develop micro-macro parameter mapping functions. The particle size for instance, a very important DEM parameter, must be chosen carefully. Choosing the particle size for a given model will always has a great deal of trade-off between simulation accuracy and computational cost. Special attention had been given to this matter; the particle size distribution is established for a given model in a way to ensure highest simulation accuracy at the lowest computational cost. This way, the model parameters (micro-mechanical properties such as friction, stiffness etc) can be linked to macro properties to achieve better physical representation.

Rocks3D^{TD} can predict the dynamic forces and flows of different discrete systems geometries under dynamic loading. As mentioned earlier, the contact parameters are micromechanical parameters that are very difficult to physically measure, and it is very challenging to evaluate because of the fact the that it is almost impossible to represent the actual shape and size of real materials. A real material is very complex to mimic in terms of shape, size, and size distributions.

The fourth approach is the MFM, which is still in a development phase. Gross distortion and eventual fragmentation of soil, which generally occur during earthmoving operations such as dozing and excavation, pose significant computational challenges to simulation by conventional Finite Element Method (FEM) [Joes report]. The main focus of this approach is to develop a 3-D earthmoving simulation code based in the use of the Mesh Free Method (MFM). This discretization method is seen as ideally suited for the prediction of implement forces and overall soil motion resulting from earthmoving operations in a fragmenting medium such as fine-grained cohesive soil. It is here, for simulations involving gross deformation and eventual fragmentation that the absence of fixed connectivity (or "mesh" as the name implies) gives MFM great flexibility, while still retaining the highly desirable characteristics of a continuum mechanics based formulation. MFM, a continuum dynamics based numerical method, is seen as ideally suited for the prediction of implement forces and overall soil motion resulting from earthmoving operations in a fragmenting medium such as fine-grained cohesive soils.

The classes of interpolation function-based discretization methods, which do not rely on fixed connectivity to describe the field variables and the instantaneous topology of the domain, have come to be known collectively as meshless methods or Mesh Free Methods (MFM). First invented in 1977, by Lucy [5] and at the same time by Gingold and Monaghan [6], the then "smoothed particle hydrodynamics method" (now called standard-SPH) was originally applied to astrophysical and cosmological problems such as star and galaxy formation. Libersky et al [7,8] extended the method to treat high-velocity dynamic response of solids and later Randles and Libersky [9] proposed significant improvements to address some of the shortcomings of standard-SPH. Since [5,6], perhaps over twenty such methods have appeared in the literature.

For the discretization of partial differential equations (PDEs) that describe a deforming medium and in particular, for problems involving gross deformation and eventual fragmentation, the absence of fixed connectivity (or mesh) is probably the most attractive general characteristic of the MFMs. These methods may be divided into two main categories based on how they discretize the equation for balance of linear momentum; those that employ a variational (or weak formulation) and those that employ a collocation (or strong formulation). This research effort focuses on one of the collocation methods -- the method of Corrected Smooth Particle Hydrodynamics (CSPH) [10,11] and how it may be adapted and applied to solving the partial differential equations that describe a deforming (and ultimately a fragmenting) medium.

The soil lab that exists in one of Caterpillar Inc. facilities has several soil bins that are being used to run scaled implement performance tests as well to collect data to validate the above mentioned numerical techniques. There are some occasions that numerical models lack the ability to handle certain operation or phenomenon. The soil lab with scaled tool size would be the alternative to resolve such issues. It is worth mentioning here that in any soil bin test, the known rules of scaling will be always applied to satisfy the physics of the problem.

SAMPLE APPLICATIONS

There are several applications that can be discussed in this section to clarify the applicability of the different numerical tools discussed above. We will in this section of the paper discuss the following application:

Bucket Loading Application

There are several CAT machines that would often require studying their bucket loading capabilities (Wheel loaders, Hydraulic Excavators, Backhoe loaders, Compact track and multi-terrain loaders, Industrial loaders, etc.). In such applications and to understand the overall machine performance, structural loads and fuel efficiency, it is essentially required to build a robust full machine virtual model. This model is potentially used to eliminate or reduce the amount of full machine field testing, which can be time consuming and quite expensive. Rocks3D^{TD} has proven that it is capable of modeling this phenomenon when coupled with the machine system model digging in fine to coarse –grained materials. Figures 1 through 3 show two examples on bucket loading applications.

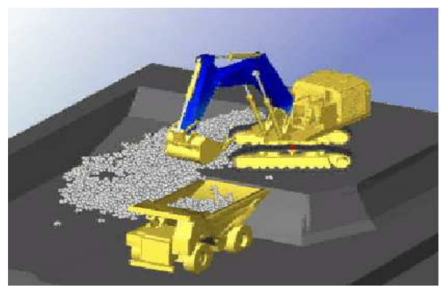

Fig. 1 . Hydraulic Excavator Bucket Loading – Dumping Operation (Granualar Material) using Rocks3D^{TD}

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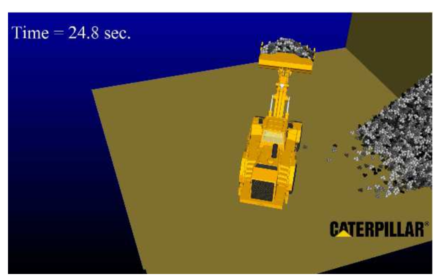

Fig. 2 . Large Wheel Loader Bucket Loading – Dumping Operation (Cohesive Material) using Rocks3D^{TD}

Fig. 3 . Medium Wheel Loader Bucket Loading – Dumping Operation (Granualar Material) using Rocks3D[TD]

Blading Operations:

There are several of Caterpillar machines (wheeled and tracked) that have the blading functionality and would often need to investigate the performance of their blades utilizing the existing numerical tools described earlier in this paper. Wheel tractor scrapers, tracked – type tractors, Motorgraders and wheeled dozers are some of the example machines that can be listed here. Figures 4 through 6 are some examples

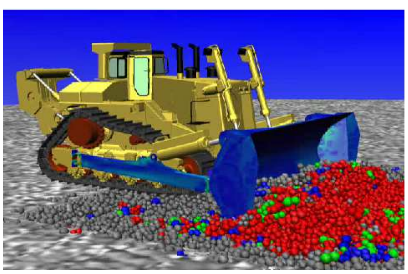

Fig. 4. D11 Track –Type Tractor Dozing Operation in Coehsive Soil using Rocks3D[TD]

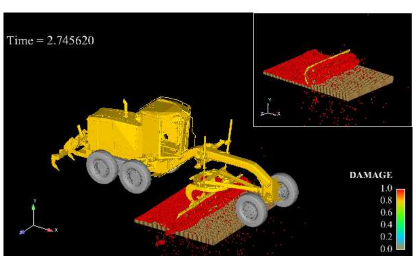

Fig. 5. Motor Grader M160 Fine Dozing Operation in Cohesive Material using MFM

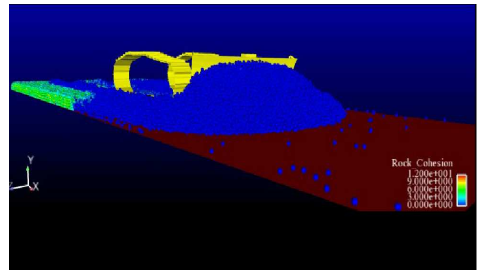

Fig. 6. D7 Track – Type Tractor Dozing Operation in Granular Material using Rocks3D

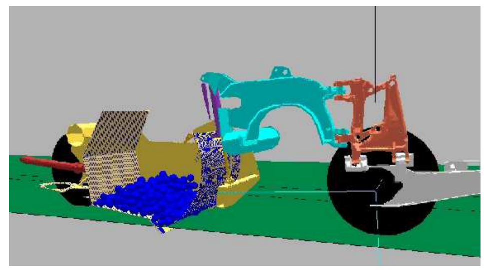

Fig. 7. Wheel Tractor Scraper 627 Loading – Unloading Operation In Rocks3D[TD] and Analytic Cutting Edge Froces Model

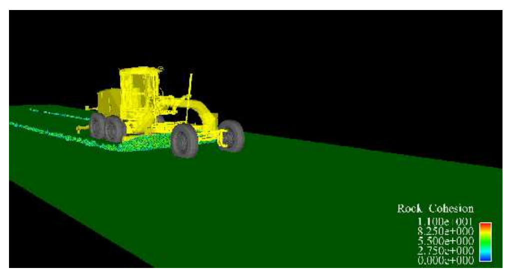

Fig. 8. Motor Grader M160 Doszing Operation in Cohesive Materials using Rocks3D[TD] and Analytic Approach for the Cutting Edge Forces.

Ripping Operations:

Caterpillar produces different types and sizes of ripper-equipped machines, these rippers essentially can operate in different types of soils and rocks. Machine performance and ripper structural life are usually the main purpose of a ripping virtual model, for those goal to be achieved, ripping forces need to be accurately predicted. Figures 9 and 10 show two examples where Rocks3D[TD] and MFM have been used to predict ripping forces.

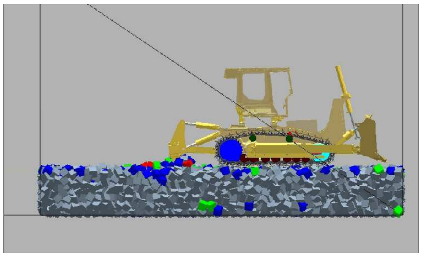

Fig. 9. D7 Track –Type Tractor Ripping Operation in a Bedrock using Rocks3D^{TD}

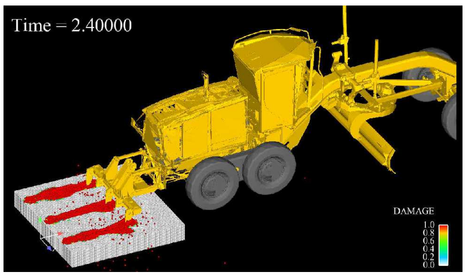

Fig. 10. Motor Grader M160 3-Shank Ripping Operation in Cohesive Soil using MFM

Tire /Wheel– and Track Mobility:

The different machines produced by Caterpillar are even tracked or wheeled machines, in either case, mobility models are needed to be able to capture their interaction with ground given the soil conditions and terrain topography. For this purpose, track –soil models and 3D tire model have been developed and implemented within the machine multi-body dynamics code (developed and owned by Caterpillar). Moreover, compaction operations are usually needed to be modeled to understand soil and landfill compaction efficiency when these machines are used. The following examples show the applications of these models. All of the above shown wheeled machine simulations use the 3D tire model

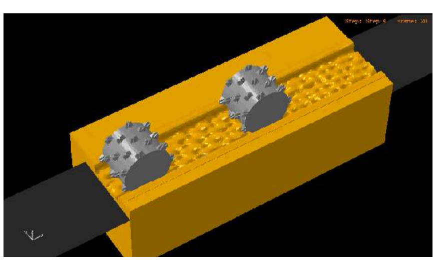

Fig. 11. Landfill Compaction Simulation using ABAQUS with an in-house developed UMAT.

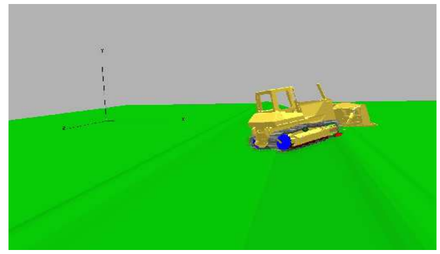

Fig. 12. Track Mobility Simulation for a D7 Tractor on an Irregular Terrain.

Soil Lab Testing and Model Validation:

The soil lab located at the Caterpillar Inc. Technical Center Facility in Mossville, IL has different soil bins. These soil bins are designed and equipped to be able run scaled tests for most of the above mentioned operations. The purpose of these scaled tests is usually to cover the gaps that some of the numerical tools have and to obtain data for the sake of model validation. Moreover, conventional triaxial tests are sometimes used to obtain full machine model parameters. Figures 13 and 14 below show some examples on both CAT soil lab tests and triaxial test validation.

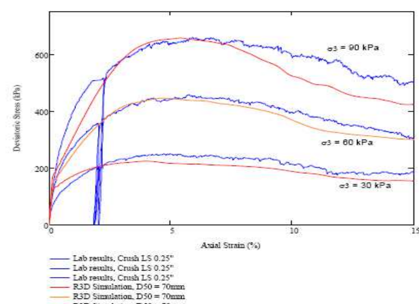

Fig. 13. Comparison between Rocks3D^{TD} and laboratory triaxial tests

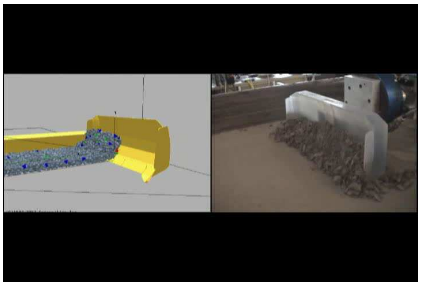

Fig. 14. Comparison between Scaled Blade Dozing Operation in the Soil Lab and the Virtual Dozing Operation in Rocks3D[TD]

CONCLUSION

Different numerical tools can be used to model the dynamic behavior of Geomaterials. FEM; DEM; MFM and Analytical Methods have been used by Caterpillar to model the different earthmoving operations. To date, reasonable results have been obtained and helped in resolving some design issues. However, lower cost and more accurate methods are always needed.

ACKNOWLEDGMENT

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