GeoMFree$^{3D}$: An Under-Development Meshfree Software Package for Geomechanics

Gang Mei$^1$, Nengxiong Xu$^1$, Liangliang Xu$^1$, and Yazhe Li$^1$

School of Engineering and Technology, China University of Geosciences (Beijing), 100083, Beijing, China
{gang.mei; xunengxiong; liang.xu; liyazhe}@cugb.edu.cn

Abstract. This paper briefly reports the GeoMFree$^{3D}$, a meshfree / meshless software package designed for analyzing the problems of large deformations and crack propagations of rock and soil masses in geotechnics. The GeoMFree$^{3D}$ is developed based on the meshfree RPIM, and accelerated by exploiting the parallel computing on multi-core CPU and many-core GPU. The GeoMFree$^{3D}$ is currently being under intensive developments. To demonstrate the correctness and effectiveness of the GeoMFree$^{3D}$, several simple verification examples are presented in this paper. Moreover, future work on the development of the GeoMFree$^{3D}$ is introduced.

1 Introduction

In geotechnics, the large deformations of rock and soil masses commonly occur in various geo-disasters such as landslides, debris flows, rock collapses, and ground subsidence. Moreover, when analyzing the stability of rock or soil slopes, the distribution and propagation of natural cracks is one of the most crucial issues that needs to be considered. To understand the mechanisms behind the above-mentioned geo-disasters, physical experiments and numerical investigations are commonly employed in practice.

The large-deformations and crack propagations of rock and soil masses have been examined using various mesh-based or meshfree numerical methods [1,2,3,4,5,6]. When employing those mesh-dependent numerical analysis methods such as Finite Element Method (FEM), Finite Volume Method (FVM), Finite Difference Method (FDM) to analyze the large deformation or crack propagation in geotechnics, the mesh element would generally be distorted or need to be broken. Mainly motivated by addressing those problems mentioned above occurring in mesh-based methods, the meshfree / meshless methods such as SPH, MLPG, LBIM, EFG, RPIM are proposed; see several excellent reviews [7,8,9].

Recently, there are several meshfree software packages that have been developed or are being under development. For example, Hsieh and Pan described the Essential Software Framework for Meshfree methods (ESFM) [10]. Cercos-Pita [11] introduced the AQUAgpusph, a new free 3D SPH solver accelerated with OpenCL. Sinaie et al [12] presents the implementation of the material point method (MPM) using Julia. Winkler et al [13] introduced gpuSPHASE, a shared memory caching implementation for 2D
SPH using CUDA. Vanaverbeke et al.\textsuperscript{[14]} presented GRADSPMHD, a completely Lagrangian parallel magnetohydrodynamics code based on the SPH formalism. Zhang et al.\textsuperscript{[15,16,17]} developed the 3D explicit parallel MPM code, MPM3D.

This short paper briefly reports the GeoMFree\textsuperscript{3D}, a meshfree / meshless software package for Geomechanics. The objective for developing the GeoMFree\textsuperscript{3D} is to numerically analyze large deformations\textsuperscript{[18,19,20]}, and crack propagations\textsuperscript{[21,22]} of rock and soil masses in geomechanics. The package GeoMFree\textsuperscript{3D} is currently under intensive developments. The underlying algorithm behind the GeoMFree3D is the Radial Point Interpolation Method (RPIM) proposed by Liu G.R.\textsuperscript{[23,24]} . In addition, to improve the computational efficiency when analyzing large-scale problems\textsuperscript{[25]}, the GeoMFree3D is parallelized on multi-core CPU and many-core GPU using the OpenMP\textsuperscript{[26]} and CUDA\textsuperscript{[27]}, respectively.

2 GeoMFree\textsuperscript{3D}

The GeoMFree\textsuperscript{3D} is a meshfree software package designed for numerically analyzing the large deformations and crack propagations of rock and soil masses in geomechanics. The GeoMFree\textsuperscript{3D} is currently capable of analyzing linear and nonlinear static problems, and is being developed for addressing dynamic problems. The GeoMFree\textsuperscript{3D} is written in C/C++ and accelerated by exploiting the parallel computing on multi-core CPU and many-core GPU.

The process of numerical modeling using the GeoMFree\textsuperscript{3D} is illustrated in Figure 1. There are three major stages in the GeoMFree\textsuperscript{3D}. The first stage is to assemble the global stiffness matrix by looping over all field nodes to create the element stiffness matrix of each field node. The second is to enforce the boundary conditions. And the third is to solve the system equation to obtain displacements and then the stresses, etc.

To improve the computational efficiency, the first stage of assembling the global stiffness matrix is parallelized on multi-core CPU using the API OpenMP\textsuperscript{[26]}. The meshfree RPIM is inherently suitable to be parallelized since there is no data dependencies between the forming of any two element stiffness matrices for any pair of field nodes. That is, the assembly of the element stiffness matrix of one field node is completely independent of that for another field node. Therefore, we can allocate n threads on the multi-core CPU; and each thread is responsible for assembling the element stiffness matrix for one field node. In this case, the assembly of element stiffness matrices for n field nodes can be conducted concurrently. This is the essential idea behind parallelizing the assembly of global / system stiffness matrix on multi-core CPU.

Similarly, to enhance the computational efficiency, the second stage of enforcing the boundary condition can also be parallelized. More specifically, we adopt the penalty function method to enforce the displacement boundary conditions. This procedure is performed in parallel on the many-core GPU. Assuming there are m field nodes on the displacement boundary, and we can allocate m GPU threads to enforce the displacement boundary conditions for the m field nodes concurrently, where each thread takes responsibility for enforcing the displacement boundary condition for one boundary field node.
The final stage is the solving of system equations to obtain nodal displacements and then the stresses. In meshfree RPIM, the assembled global stiffness matrix is large, sparse, and asymmetric. When analyzing large-scale problems and requiring a large number of field nodes, the global system matrix could be very large. To improve the computational efficiency in solving system equations, we have employed the cuSparse and cuSolver library integrated in CUDA [27] to solve the system of equations.

Fig. 1. Process of our meshfree software package GeoMFree\textsuperscript{3D}
3 Verification

This section will present several computational examples to verify the validation and features of the reported meshfree software package GeoMFree$^{3D}$.

3.1 Example 1: Stresses of a Cubic Domain

First, to verify the correctness of the GeoMFree$^{3D}$, we specifically calculate the distribution of displacements and stresses of a cubic domain; see Figure 2. In this quite simple verification example, only the force of gravity is considered and there are no other forces. The density of the cube is set as 2600 kg / m$^3$. The stress on the bottom of the cube can be theoretically calculated, and is noted as the theoretical result. In contrast, we can also numerically calculate the nodal stress on the bottom using our meshfree package GeoMFree$^{3D}$ which is noted as the numerical result. Then, by comparing the theoretical result to the numerical counterpart, we could validate the correctness of the GeoMFree$^{3D}$.

The theoretical nodal stress on the bottom of the cube is 2.548 MPa, while the numerically calculated one is 2.376 MPa. There is a slight difference between the theoretical and numerical results. And thus, we can conclude that the correctness of the GeoMFree$^{3D}$ has been verified, although the employed verification example is extremely simple.

![Fig. 2. Verification example 1: stresses of a cubic domain. (a) Computational model of a cubic domain; (b) Stresses calculated by using our package GeoMFree$^{3D}$.](image)

3.2 Example 2: Displacements of a Cantilever Beam with Crack

To further verify the effectiveness of our GeoMFree$^{3D}$, we have employed it to calculate the displacement and stress field of a Cantilever beam with a crack; see Figure 3.
Moreover, we have also computed the displacements and stresses of the beam using a FDM numerical software FLAC\textsuperscript{3D}; see Figure 3(b). The numerical results calculated by our package GeoMFree\textsuperscript{3D} and the commercial numerical software FLAC\textsuperscript{3D} are almost the same; see Figure 3(b) and 3(c). And this indicates that currently our package GeoMFree\textsuperscript{3D} is capable of analyzing the very simple cases of crack propagation. In the near future, we hope that the GeoMFree\textsuperscript{3D} can be used to model and simulate dynamic crack propagations in three-dimensions.

### 3.3 Example 3: Displacements of a Simplified Slope

As having been introduced several times, the motivation why we are developing our meshfree package GeoMFree\textsuperscript{3D} is that: we hope to employ one of the meshfree methods, i.e., the RPIM, to well model and simulate the large deformations and crack propagations of rock and soil masses. Currently, the GeoMFree\textsuperscript{3D} cannot be used to model the continuously developed large deformations of rock or soil masses. But it can be used to calculate the displacements of a simplified slope; see Figure 4 and Figure 5. And we are working on analyzing the stability of slopes using the GeoMFree\textsuperscript{3D} based upon the Strength Reduction Method (SRM).

In meshfree methods, the study domain is discretized with a set of field nodes. These field nodes could be (1) regularly or (2) irregularly distributed in the domain. The patterns of nodal distributions are of strong influence on both the computational accuracy and efficiency. To verify the flexibility of the GeoMFree3D for addressing problems with regular or irregular discretization, we have decomposed a simplified slope model with: (1) regular nodes (Figure 4(b)) and (2) irregular nodes (Figure 5(a)). We then calculated the displacements of the above two models using our package GeoMFree\textsuperscript{3D}, and also compared the results calculated by the GeoMFree\textsuperscript{3D} to those by the commercial software FLAC\textsuperscript{3D}.

The numerical results illustrated in Figure 4 and Figure 5 indicate that: (1) our package GeoMFree\textsuperscript{3D} is capable of analyzing the problems with regular or irregular nodal distributions; (2) our package GeoMFree\textsuperscript{3D} can be used to address the problems with relatively complex geometric domains and boundaries.

### 4 Conclusion and Future Work

A meshfree software package, GeoMFree\textsuperscript{3D}, has been briefly introduced in this paper. The package GeoMFree\textsuperscript{3D} is designed for the numerical investigation of large-deformations and crack propagations of rock and soil masses in geotechnics. The GeoMFree\textsuperscript{3D} is developed based on the RPIM, and is currently under intensive developments. To validate the effectiveness of the introduced GeoMFree\textsuperscript{3D}, several verifications have been conducted. The verification examples have demonstrated that the current version of GeoMFree\textsuperscript{3D} is capable of analyzing the deformation of simple study domains.

The GeoMFree\textsuperscript{3D} is currently under intensive developments. We are focusing on improving the computational efficiency by developing accurate and efficiency meshfree shape functions\textsuperscript{[28,29,30]}, for example, the parallel RBF\textsuperscript{[31]}, MLS\textsuperscript{[32]}, and Shepard\textsuperscript{[33,34]} interpolations. Currently, we are also aiming at numerically modeling the crack
Fig. 3. Verification example 2: displacements of a Cantilever beam with crack
Fig. 4. Displacements of a simplified slope when employing regularly-distributed field nodes
propagation of multiple tensile and shear cracks of rock masses. In future, we hope that: the GeoMFree\textsuperscript{3D} can be used to (1) model the large-deformations of strata induced by underground mining and (2) analyze the stability of jointed rock slopes via modeling the very complex crack propagations of rock masses.

\textbf{Fig. 5.} Displacements of a simplified slope when employing irregularly-distributed field nodes
Acknowledgements

This research was supported by the Natural Science Foundation of China (Grant Numbers 41772326 and 11602235), and the Fundamental Research Funds for the Central Universities. The authors would like to thank the editor and reviewers for their contributions on the paper.

References

1. Soga, K., Alonso, E., Yerro, A., Kumar, K., Bandara, S.: Trends in large-deformation analysis of landslide mass movements with particular emphasis on the material point method. Geotechnique 66(3) (2016) 248–273
2. Bhandari, T., Hamad, F., Moormann, C., Sharma, K.G., Westrich, B.: Numerical modelling of seismic slope failure using mpm. Computers and Geotechnics 75 (2016) 126–134
3. Huang, P., Li, S.L., Guo, H., Hao, Z.M.: Large deformation failure analysis of the soil slope based on the material point method. Computational Geosciences 19(4) (2015) 951–963
4. Wang, B., Vardon, P.J., Hicks, M.A.: Investigation of retrogressive and progressive slope failure mechanisms using the material point method. Computers and Geotechnics 78 (2016) 88–98
5. Ullah, Z., Coombs, W., Augarde, C.: Parallel computations in nonlinear solid mechanics using adaptive finite element and meshless methods. Engineering Computations 33(4) (2016) 1161–1191
6. Huang, Y., Zhu, C.Q.: Simulation of flow slides in municipal solid waste dumps using a modified mps method. Natural Hazards 74(2) (2014) 491–508
7. Nguyen, V.P., Rabczuk, T., Bordas, S., Duflot, M.: Meshless methods: A review and computer implementation aspects. Mathematics and Computers in Simulation 79(3) (2008) 763–813
8. Liu, G.R.: An overview on meshfree methods: For computational solid mechanics. International Journal of Computational Methods 13(5) (2016)
9. Chen, J.S., Hillman, M., Chi, S.W.: Meshfree methods: Progress made after 20 years. Journal of Engineering Mechanics 143(4) (2017) 04017001
10. Hsieh, Y.M., Pan, M.S.: Esfm: An essential software framework for meshfree methods. Advances in Engineering Software 76 (2014) 133–147
11. Cercos-Pita, J.L.: Aquagpusph, a new free 3d sph solver accelerated with opencl. Computer Physics Communications 192 (2015) 295–312
12. Sinaie, S., Nguyen, V.P., Nguyen, C.T., Bordas, S.: Programming the material point method in julia. Advances in Engineering Software 105 (2017) 17–29
13. Winkler, D., Meister, M., Rezavand, M., Rauch, W.: gpusph: a shared memory caching implementation for 2d sph using cuda. Computer Physics Communications 213 (2017) 165–180
14. Vanaverbeke, S., Keppens, R., Poedts, S.: Gradspmhd: A parallel mhd code based on the sph formalism. Computer Physics Communications 185(3) (2014) 1053–1073
15. Liang, Y., Benedek, T., Zhang, X., Liu, Y.: Material point method with enriched shape function for crack problems. Computer Methods in Applied Mechanics and Engineering 322 (2017) 541–562
16. Chen, Z.P., Zhang, X., Qiu, X.M., Liu, Y.: A frictional contact algorithm for implicit material point method. Computer Methods in Applied Mechanics and Engineering 321 (2017) 124–144
17. Zhang, F., Zhang, X., Sze, K.Y., Liang, Y., Liu, Y.: Improved incompressible material point method based on particle density correction. International Journal of Computational Methods 0(0) (2018) 1850061

18. Goodarzi, M., Rouainia, M.: Modelling slope failure using a quasi-static mpm with a non-local strain softening approach. Procedia Engineering 175 (2017) 220–225

19. Huang, Y., Dai, Z.L.: Large deformation and failure simulations for geo-disasters using smoothed particle hydrodynamics method. Engineering Geology 168 (2014) 86–97

20. Dai, Z.L., Huang, Y., Cheng, H.L., Xu, Q.: 3d numerical modeling using smoothed particle hydrodynamics of flow-like landslide propagation triggered by the 2008 wenchuan earthquake. Engineering Geology 180 (2014) 21–33

21. Zhou, X.P., Bi, J.: 3d numerical study on the growth and coalescence of pre-existing flaws in rocklike materials subjected to uniaxial compression. International Journal of Geomechanics 16(4) (2016)

22. Bi, J., Zhou, X.P., Xu, X.M.: Numerical simulation of failure process of rock-like materials subjected to impact loads. International Journal of Geomechanics 17(3) (2017) Bi, Jing Zhou, Xiao-Ping Xu, Xiao-Min.

23. Liu, G.R., Zhang, G.Y., Gu, Y.T., Wang, Y.Y.: A meshfree radial point interpolation method (rpim) for three-dimensional solids. Computational Mechanics 36(6) (2005) 421–430

24. Liu, G.R., Li, Y., Dai, K.Y., Luan, M.T., Xue, W.: A linearly conforming radial point interpolation method for solid mechanics problems. International Journal of Computational Methods 3(4) (2006) 401–428

25. Borin, E., Devloo, P.R.B., Vieira, G.S., Shauer, N.: Accelerating engineering software on modern multi-core processors. Advances in Engineering Software 84 (2015) 77–84

26. : OpenMP (2018)

27. NVIDIA: CUDA (2018)

28. Cavoretto, R., De Rossi, A.: Spherical interpolation using the partition of unity method: An efficient and flexible algorithm. Applied Mathematics Letters 25(10) (2012) 1251–1256

29. Cavoretto, R., De Rossi, A.: A meshless interpolation algorithm using a cell-based searching procedure. Computers & Mathematics with Applications 67(5) (2014) 1024–1038

30. Cavoretto, R., De Rossi, A., Perracchione, E.: Efficient computation of partition of unity interpolants through a block-based searching technique. Computers & Mathematics with Applications 71(12) (2016) 2568–2584

31. Ding, Z., Mei, G., Cuomo, S., Xu, N., Tian, H.: Performance evaluation of gpu-accelerated spatial interpolation using radial basis functions for building explicit surfaces. International Journal of Parallel Programming (2017)

32. Merry, B., Gain, J., Marais, P.: Moving least-squares reconstruction of large models with gpus. Ieee Transactions on Visualization and Computer Graphics 20(2) (2014) 249–261

33. Mei, G., Xu, N.X., Xu, L.L.: Improving gpu-accelerated adaptive idw interpolation algorithm using fast knn search. Springerplus 5 (2016)

34. Mei, G., Xu, L.L., Xu, N.X.: Accelerating adaptive inverse distance weighting interpolation algorithm on a graphics processing unit. Royal Society Open Science 4(9) (2017)