STRUCTURE LAYER MODEL IN CONTINUUM-DISCONTINUUM ELEMENT METHOD

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A new interface model for discrete element method, named structure layer model, is introduced. Structure layer is composed of spring elements and adopted to continuum-discontinuum element method, CDEM. It is with thickness but without mass. Thin intercalation in the discontinuous geologic bodies as well as the interface between elements in the continuous problem can be modeled by structure layer. Different from the traditional interface spring model in discrete element method, the stiffness of structure layer has definite physical meaning, because the layer is with real thickness and all the parameters are determined by the factual material. Not only tension and shear, but also Poisson effect and pure shearing can be expressed with structure layer model, which increases the accuracy of numerical modeling for thin structure layer. Meanwhile, since there is no need to set large spring stiffness to ensure displacement continuity of nodes at the same place as in the interface spring model, large time step can be adopted, efficiency of computation is increased

INTRODUCTION

Discrete element method(DEM) has been wildly used in many engineering and scientific fields, due to its great advantage to simulate problems related to contact and motion. So DEM is an useful tool to describe discontinuous surfaces such as joints, fissures and weaken layers which widely exist in geological media and other materials with Complicated characteristics. Since originally applied to problems in rock mechanics by Cundall[1] in 1971, there has been lots of developments in DEM. Three-dimensional DEMs with polyhedral blocks are developed by Cundall[2] and Hart[3] at el. in 1988. Later, a combined finite－discrete element model were proposed by Munjiza et al[4] . Owen et al[5] reviewed computational strategies in the context of combined discrete/finite element methods for effective modeling of large-scale practical problems involving multiple fracture and discrete phenomena in 2004. Latham et al used 3D laser ranging capture realistic rock aggregate geometries and developed algorithm to generate computationally meshed virtual particles for modeling. Although varies new methods were established to deal with mixed continuous-discrete problems or whole process problems, DEM still plays an important role on its own or being part of these new methods.

However, there exists a fatal problem that has plagued scholars for long time. The spring stiffness, which has been artificially applied to interface of particles or blocks, is doubted and criticized by scholars because its physcial meanings is not clear. In DEM, spring can be used as bond of particles and blocks to ensure continuum of particles and nodes of numerical structure in initial continuous stage. Usually, stiffness must be set large enough to satisfy continuity condition of displacement. But time step and stiffness have inverse relationship. Large stiffness may case time wasting and low efficiency. Low stiffness could improve computational efficiency and has little influence of force or stress, but will leads to larger displacement. Accuracy of numerical result could not be obtained.

Another problem caused by interface spring is energy. In a given numerical model, elastic potential energy of the whole system is the elastic potential energy sum of all the elements, As we know that springs with high stiffness on interface could satisfy continuity condition of displacement, but brings extra elastic energy. These energy should not exist in the system.

The aim of this paper is to introduce a new interface model, named structure layer model, which give clear physical meaning to interface springs. This new model has been added to continuum-discontinuum element method[7,8], and wildly used to simulate various engineering problems with progressive failure process. In the beginning, continuum-based discrete element method is briefly introduced. Then, geometrical configuration and theory of structure layer are presented in detail. In the end, verification and numerical cases are given.

CONTINUUM-DISCONTINUUM ELEMENT METHOD

Continuum-discontinuum element method (CDEM) is originally proposed by Li et al.[7]. The earlier model was called continuum-based discrete element method which is a combination of finite element and discrete element method. Geometrical concept in CDEM is shown in fig.1.

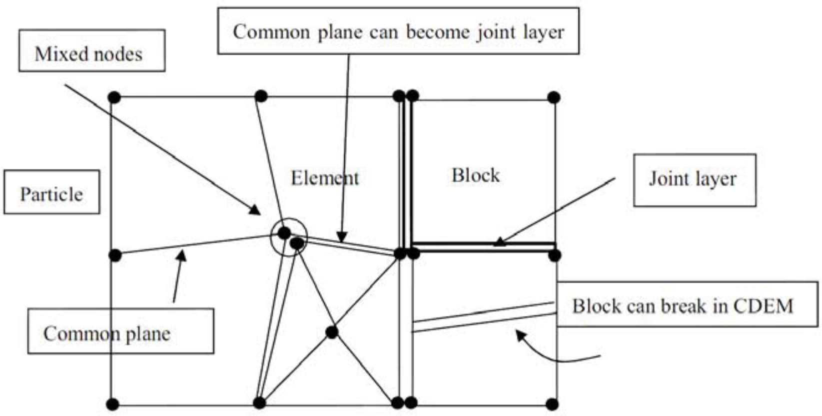

Fig 1. Geometrical concept of CDEM

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A block is cut by physical face in rock mass or in materials. A polyhedron block consists of several tetrahedrons. Element is cut using mathematical method. Elements can become blocks in CDEM. The main difference between elements and blocks is that there are no joint, faces or joint layers between neighboring blocks. A block can consist of several elements. Common face or element face represents face which is shared by two elements. Joint face represents the face between neighboring blocks which dose not belong to any block. Joint layer is between neighboring blocks with thickness. Particle means A point with mass. Node is a point marking a position on which several particles can be. The node is called continuous node when all particles on it belong to elements and is called mixed node when the particles on it are from both elements and blocks. The node is called distinct node when all particles on it are from blocks.

Governing equations of CDEM can be expressed as

$$m^i \ddot{\vec{u}}^i + c_m \dot{\vec{u}}^i = \vec{F}^E + \vec{F}^I + \vec{F}_b^d + \vec{F}_b^c + \vec{F}_j^d + \vec{F}_j^c \tag{1}$$

$$I^i \ddot{\vec{\theta}}^i + C_I r_0^2 \dot{\vec{\theta}}^i = \vec{M}^E + \vec{M}^I + \vec{M}_j^d + \vec{M}_j^c \tag{2}$$

Where $\ddot{\vec{u}}^i$ is acceleration, $\dot{\vec{u}}^i$ is velocity, m^i is the mass of i_{th} particle, c_m is the damping of particle, $\vec{F}^E$ is external force, $\vec{F}^I$ is body force, $\vec{F}_b^d$ is deformation force of block, $\vec{F}_b^c$ is damping force of block, $\vec{F}_j^d$ is deformation force of spring, $\vec{F}_j^c$ is damping force of spring, $\ddot{\vec{\theta}}^i$ is angular acceleration, $\vec{\theta}^i$ is angular velocity, I^i is rotational inertia, r_0^2 is radius vector, $\vec{M}^E$ is external moment, $\vec{M}^I$ is internal moment, $\vec{M}_j^d$ is moment of damping, $\vec{M}_j^c$ is moment of deformation.

STRUCTURE LAYER MODEL IN CDEM

Structure layer model is established to simulate joint layer or even common face. Two steps are adopted including face indent and construction of thin layer spring element.

Face indent. Joint layer or common face should indent to construct a thin layer with thickness according to the practical problem. Indented face should parallel to the original face. Then a thin layer is formed between two elements as shown in fig 2.

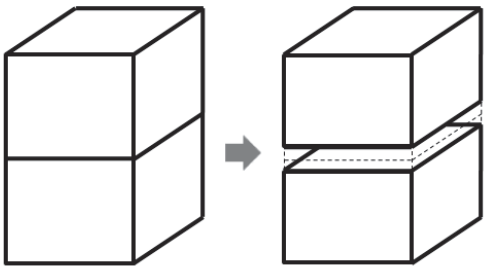

Fig 2. Indent of face

Thin layer spring element. The thin layer indented above will be filled by spring element, which is a new type thin layer element developed from spring element originally proposed by Li at el. The geometry of the element is shown in fig 3.

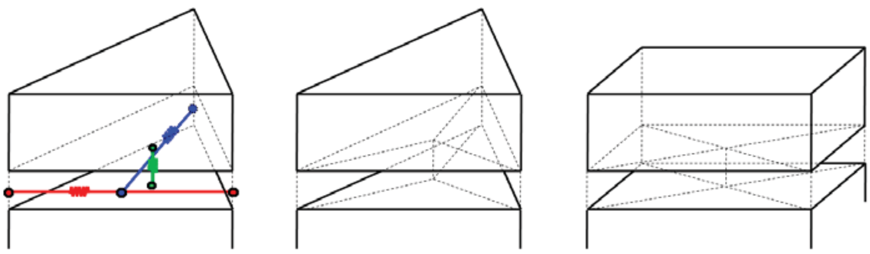

Fig 3 spring element of structure layer model

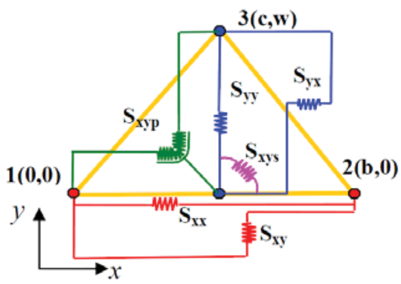

Fig 4 Spring system of three-node triangular element by Li at el.

Thin layer spring element is composed of a triangle spring element shown as fig 4. and a thickness spring. Stiffness of each spring is determined according to the material. Poisson and pure shear effect of each spring is considered. A structure layer can consist of only one spring element, three spring element or four spring element according to accuracy demand and shape of the layer.

Structure layer element can break itself when exceeded its strength, and only three basic springs left including the normal spring and two shear spring to describe contact and friction.

VERIFICATION AND APPLICATION OF STRUCTURE LAYER MODEL AND CDEM

Structure layer model has been added to CDEM code developed by Li at el.. In this section, single structure layer and multi structure layers were verified and some numerical cases were given.

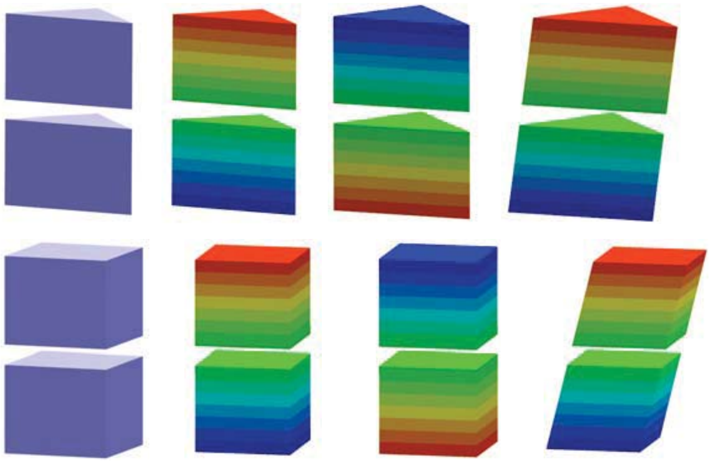

Fig 5 cloud map of displacement under different load condition

Table 1 parameter of the model

E	*v*	Pressure	Length	Width	Height	Indent
1.0e10Pa	0.25	1MPa	1m	1m	2m	0.2

Table 2. Result of a single structure layer

Model	Tension	Compression	shear
pentahedron	2e-4m	-2e-4m	5e-4m
hexahedron	2e-4m	-2e-4m	5e-4m
Theoretical	2e-4m	-2e-4m	5e-4m

In this simple case, tension, compression and shear load are tested. Cloud map of displacement are shown in fig.5. Parameters used in this model are listed in table 1. With structure layer, numerical results and theoretical results are highly consistent.

Multi structure layer case are tested to verify the adaptability of the model. Structure layers with different thickness and directions are set in the numerical model. Cloud map of displacement are shown in fig. 6. Parameters are listed in table 3 and numerical results are listed in table 4. Numerical results agree with the theoretical results.

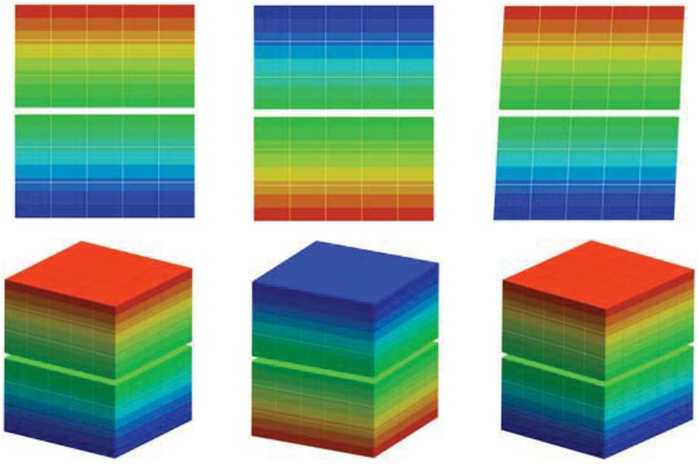

Fig. 6 Cloud map of displacement for multi structure layer case

Table 3 parameter of the multi structure layer case

E	v	Pressure	Length	Width	Height	Indent-1	Indent-2
1.0e10Pa	0.25	1MPa	10m	10m	12m	0.2	0.01

Table 4. Result of multi structure layer case

	Tension	Compression	Shear
Numerical	1.20e-3m	-1.20e-3m	3.00e-3m
Theoretical	1.20e-3m	-1.20e-3m	3.00e-3m

Other more numerical cases are shown in fig. 7, fig 8 and fig 9.

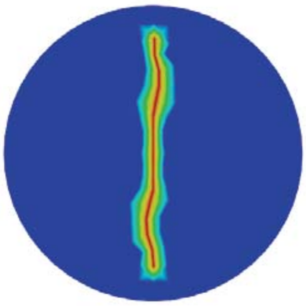

Fig.7 Simulation of Brazilian splitting test

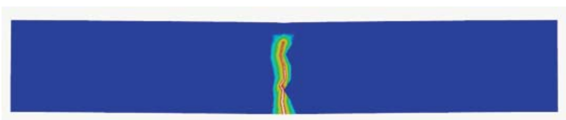

Fig.8 Simulation of three-point-bend beam

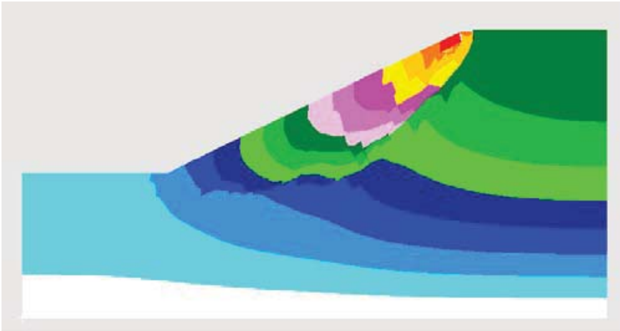

Fig.9 Simulation of crack in a slope

CONCLUSION

Structure layer model is a new thin layer model or interface model, which gives clear physical meaning to the interface stiffness. With this model, no extra energy was added in the system, and relatively large time step could be adopted without loss the accuracy of displacement. The model has been added to CDEM code, and numerical results are highly consistent with real solution.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of National Program on Key Basic Research Project (973 Program, Grant No. 2010CB731500).

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