Nonlinear structural subsystem of GeoFEM for fault zone analysis

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Abstract

Solid earth has very complex dynamics, which are material nonlinearity of plates, large deformation of plates, contact and large slip of complex fault network and complex friction law of faults. Solid earth demands sophisticated nonlinear structural analysis method. In those dynamics the fault zone dynamics is very important. Mechanical and civil engineering has developed the sophisticated method of nonlinear structural analysis [1] [2] [3] [4] [5] . So we use nonlinear structural analysis method of mechanical and civil engineering for the development of GeoFEM at the start. But in solid earth analysis, the further development of analysis method is needed.

Introduction

Solid earth has very complex dynamics [6], which are material nonlinearity, geometrical nonlinearity, time dependency (quasi statics phenomena for a long period) and multi-phase dynamics. And GeoFEM uses not only continuum model but also discontiuum one. The discontinuum model handles a fault model, which is very complex contact problem and very inportant dynamics. So highly stabilized nonlinear analysis method is needed in GeoFEM.

Solid earth complexity

Material nonlinearity

Solid earth material behavior depends on time scale and depth. For a very short time interval (from a few seconds to a few minutes), solid earth responds as elastic solid material. But a long time interval (from a few millions to a few ten millions years), solid earth responds as viscous elastic solid material. For a very long time interval (a few billions years), solid earth responds as viscous elastic fluid, or viscous fluid material. Otherwise, The material character varies depending on the depth. The superficial parts of plates have an elastic-plastic solid character. Bottoms of the crust and top of the mantle have a viscous-elastic solid character. The mantle has a viscous fluid character. Micro earthquake is considered as micro faults failure. Coulomb

Failure Function is evaluated as micro faults failure criterion. So an advanced elastic-plastic analysis method of Mohr-Coulomb material in civil engineering is very useful for GeoFEM.

Geometrical nonlinearity large deformation analysis

In a very long period of time, plate's deformation is very large. If the period of time is 10^7 years, Pacific Sea Plate (whose moving speed is about 10 cm/year) moves at the speed of 1000 km. Plates move as mostly rigid body. But at the plate's boundary neighborhood, finite deformation exists. So a geometorical nonlinear analysis is essential.

Complex faults network analysis

Complex network

Solid earth includes enormous faults, and the scale of which varies in a very wide range. The largest fault example is faults at the plate's boundary, small faults example is cracks of rocks. It is impossible to model directly these whole faults. So approximation of modeling is acceptable. GeoFEM models small-scale faults as continuum region and large-scale faults as contact surface. Bud still, the number of large-scale faults is high and the network is very complex. Therefor, GeoFEM must solve the contact problem of the very complex network.

Large slip

In the period of 10^7 years time, slip length of faults at the plate's boundary is more than 1000 km. A joint element method is widely used for contact problem in civil engineering. But Joints element method is not applicable for a large slip problem. So, GeoFEM needs more advanced contact problem analysis method.

Complex friction law

The friction law of faults contact surface is more complex than that of mechanical engineering contact problem. The low of fault friction demands many kinds of material analysis method that are Mohl-Coulomb Failure criteria, yielding, unloading, time depending hardening and softening. For example, Fig. 1 shows a viscous elastic-plastic constitutive equation model of faults friction.

Nonlinear analysis strategy

Material nonlinear analysis method

Steep convergence algorithm is required for material strong non-linear problem. GeoFEM introduces the return-mapping algorithm. The return mapping algorithm is very robust and unified algorithm for many kinds of nonlinear material constitutive equation.

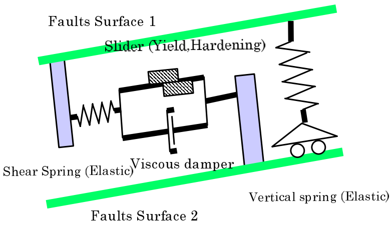

Figure 1: Viscous elastic-plastic model in faults.

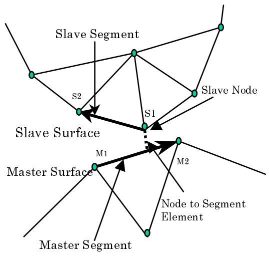

Figure 2: Node to segment model for complex faults.

Geometrical nonlinear analysis method

GeoFEM intakes the Update Lagrange method for geometrical nonlinear analysis, because of that simple system. Finally GeoFEM must handle very complex dynamics. A simple analysis algorithm is more appropriate

Complex faults network analysis method

GeoFEM uses two kinds of contact problem analysis method. One is joint element method for small slip, small deformation and regular contact surface meshing. The other is a node to segment contact model [7] for large slip, large deformation and irregular surface meshing(Fig. 2).

Nonlinear analysis method

GeoFEM uses the Newton-Raphson method that uses iterative matrix solver. Newton-Raphson method will be useful for many cases. But the convergence of iterative matrix solver and Newton-Raphson method would be difficult for a very strong nonlinear problem. That problems have the increase of matrix's condition number. Therefore GeoFEM prepares the methods which modify matrix to be able to use iterative solver for ill condition matirx. Those method are Modified Newton Method,Augmented Lagrangian Method, Dynamic Relaxation method etc.

Fault zone analysis example

Now, we are developing the prototype of GeoFEM. That prototype has a fault zone analysis function. In this paper, fault zone analysis example that includes contact, material nonlinear and gravity is shown in Fig. 3 , Fig. 4. Gravity is 9.8m/s**2. Nonlinear Material is Mohr-Coulomb Drucker-Prager model. This example problem was solved by serial,direct solver and penalty method. And the scale of that problem is small. That dofs. is 8217, but nonlinearity is very strong and its phenomena are very complex.

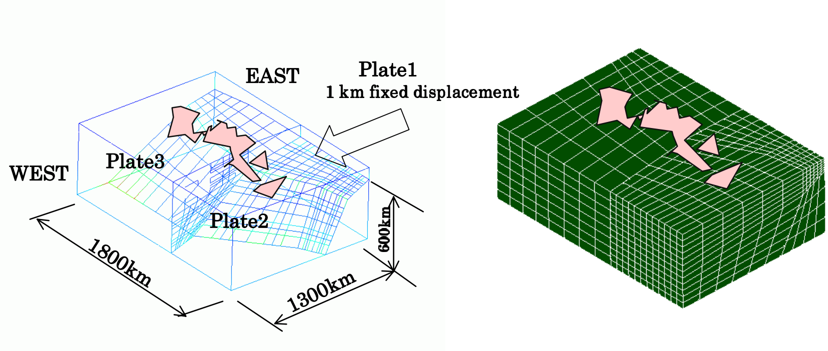

Figure 3: Analysis Model of Typical Faults Network at the 3 Plates End

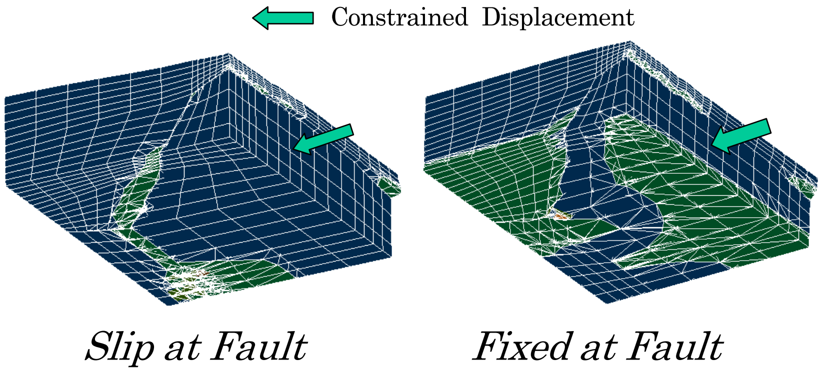

Figure 4: Equivalent Shearing Strain Contour (View from the Bottom of Plates)

Conclusion

GeoFEM handles very complex solid earth dynamics. At the start, we use the non-linear analysis method of mechanical and civil engineering for GeoFEM development. But the further development of analysis method is needed for GeoFEM. Now, we are developing the prototype code of GeoFEM complex analysis.

Acknowledgments

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References

[1] Yamada,Y., 1994, *Elastic-plastic and viscous-Elastic,* baifuukan.

[2] Hisada,T., Noguchi,H., 1995, *Basis and Application of Nonlinear analysis FEM,* maruzen.

[3] Zienkeiewicz,O.C. , Taylor,R.L., Japanese Edition,1996 *The Finite Element Method, fourth Edition,* CADTECHS, INC., Tokyo.

[4] Naylor, D.J., Pande, G.N. Simpson, B. Tabb, R., 1987, *Finite Elements in Geotechnical Engineering,* Kajima Institute Publishing.

[5] Tanaka, C., Ukai, K., others, 1996, *3 dimensional elastic-plastic FEM analysis of groud,* Kajima Institute Publishing

[6] Bird, P., 1994, *New finite element techniques for modeling deformation histories of continents with stratified temperature dependent rheology,* J. Geophys. Res. 3967-3990.

[7] Zhang,Z.H. and Mackerle,J., 1992, *Static contact problems - a review,* Engineering Computions, **9**, 3-37.