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Challenge for Forward Computer Simulation to Model Structural Deformation Coupled with Fluid Migration

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INTRODUCTION

Prediction of the development of faults and fractures, especially location and properties such as porosity and permeability is very important to evaluate generation, migration, and accumulation of oil and gas. Although it is believed that faults and fractures act as conduit and/or seal for oil and gas migration in vertical direction in sedimentary basins, understanding of the processes are not enough and hence we do not have precise tool to evaluate them.

Our challenge is to develop a computer code to model structural deformation in forward direction (process-oriented, from past to present) and are trying to couple with fluid migration. Our idea is that if fault and fracture zones are diluted due to deformation (work-softening effect), they become conduit for fluid migration, and if fault and fracture zones are compacted due to deformation (work-hardening effect), they become seal for fluid migration.

OUTLINE OF THE MODEL

(1) Elastoplastic Constitutive Law

In our model, rocks are treated as elastoplastic continuums and shear deformation and consolidation (compaction) are included. Constitutive law governing shear deformation has been studied by laboratory experiments. These results are summarized as Mohr-Coulomb criterion, Griffith criterion, and Drucker-Prager’s yield criterion for rocks, and as Cam-Clay model for clays. Consolidation (compaction) is mainly caused by gravity. But rocks are not strongly affected by gravity in laboratory scale. In soil mechanics, the behavior of soft rocks like clays are described as the elastoplastic constitutive law such as Cam-Clay model. Cam-Clay model is useful because it can treat both shear deformation and consolidation (compaction) simultaneously, and both work-softening and work-hardening effects are reproduced according to stress state. In our model, all these constitutive laws are involved, but we mainly used Cam-Clay model for our simulations and are trying to extend the Cam-Clay model originally studied in laboratory scale to geological scale.

(2) Mixed Finite Element Method Using Assumed Strain

In the process of geological deformation, discontinuous structures such as fault and fracture are important to evaluate fluid migration. Strain concentrated zone inevitably predicted by constitutive laws in complete plastic or work-softening state is regarded as a fault in this model. By means of this way, simulations can be treated completely within the scheme of elastoplastic continuum, but the simulation of strain concentration becomes a challenge. In order to overcome this, mixed finite element method using assumed strain (Simo and Armero ,1992) is adopted as a high-precision numerical method in our model.

(3) Return Mapping Algorithm

Elastoplastic constitutive law in this model is expressed by a combination of strain increment and stress increment. Accordingly, to obtain stress-state corresponding to a given deformation, it is required to integrate the constitutive equation by time through the deformation path. As a time integration method, return-mapping method on principal axes proposed by Simo (1992) is adopted. Especially for the Cam-Clay model, return-mapping method proposed by Simo and Meschke (1993) is adopted.

(4) Fluid Migration

In the current version, pore fluid is assumed as non-compressive one phase, and the Darcy's law is used for pore fluid migration. Permeablity is given as a function of porosity. If dilatancy is occurred by deformation, the increase of volume is converted to the increase of porosity and as a result, permeability increases.

APPLICATIONS TO GEOLOGICAL SCALE

We applied our model into several geological examples to understand the behavior of Cam-Clay model.

(1) Thrusting (Fig. 1)

Rock property of the Kashiwazaki-oki structure in the Niigata basin, Japan was used for this simulation (alternation of sandstone and shale). The bottom of simulated body was fixed, and lateral side was compressed horizontally from right direction. The result of the simulation with Cam-Clay model is shown in the upper part of Fig. 1, and one with Drucker-Prager model in the lower part. A fault (strain concentration zone) is reproduced more sharply with Cam-Clay model, since it can simulate work-softening effect.

(2) Salt Dome (Fig. 2)

Our model also simulated the distribution of fractures (faults) by salt intrusion. We assumed rock properties as carbonate and evaluated the sensitivity of the distribution of fractures to the shape and height of dome as well as the direction and degree of regional stress. Simulated results are consistent not only with published laboratory experiments, but also with actual 3D seismic data in a basin of Middle East.

(3) Relay Ramp

We are also studying the distribution of faults and fractures in relay ramp structure by our model.

FUTURE DEVELOPMENT

Cam-Clay model is an empirical law of infinitesimal strain conducted from laboratory scale phenomena, so that the application to geological scale is rare. Extension to finite deformation (geological scale) has not been established. In our model, Cam-Clay model is extended to finite deformation based on the formulation proposed by Borja and Tamagnini (1998). Non-linear elastic model based on swelling curve is used in Cam-Clay model, so that physically appropriate stress is limited to a fixed range. This limitation makes the extension of Cam-Clay model to geological scale difficult.

In addition, rock properties required for Cam-Clay model are not well known. Only soft rock data are studied in laboratory scale. We are testing properties of various rocks required for Cam-Clay model and are trying to determine the range for appropriate calculation by trial and error.

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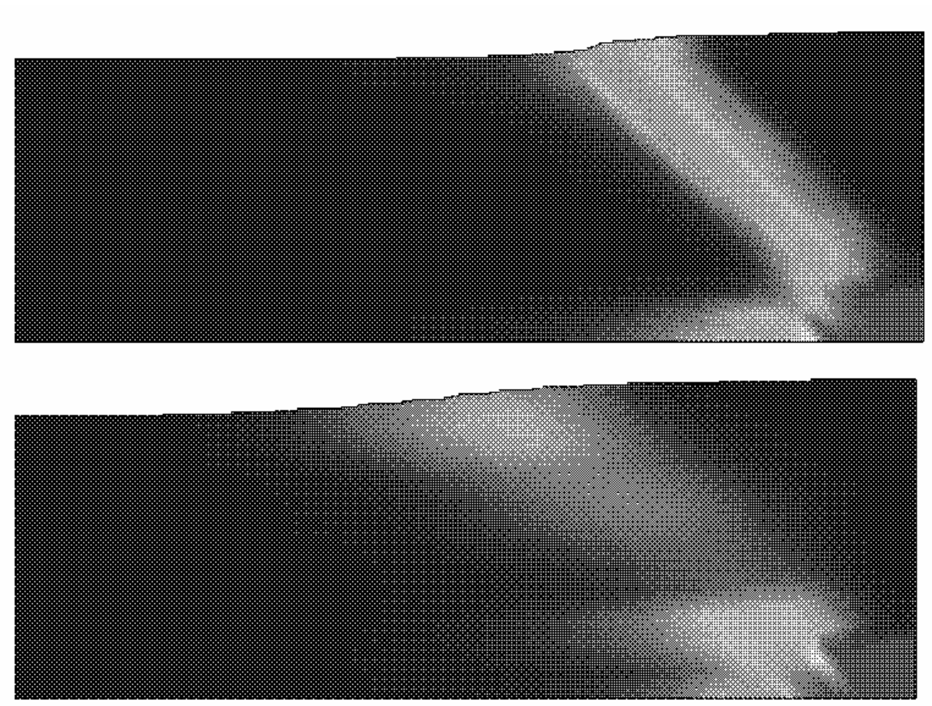

Fig.1 Comparison of Simulated Results for Thrusting
(Upper: Cam-Clay model, Lower: Drucker-Prager model)

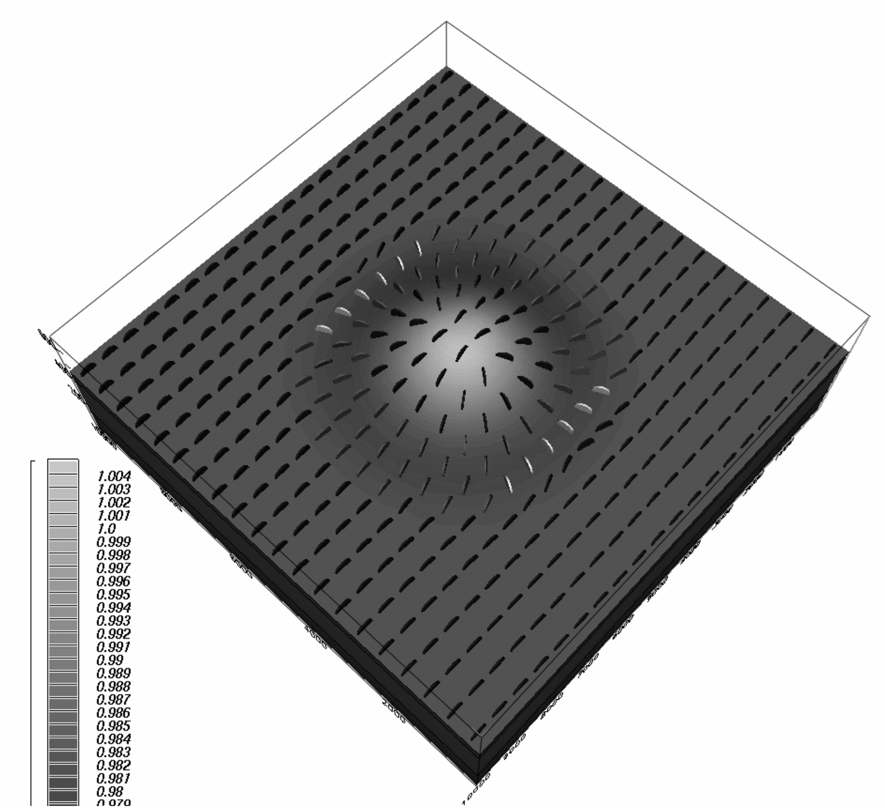

Fig. 2 Simulated Result for Salt Dome
Disks on surface indicate fracture direction.