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Discrete element simulations of continental collision in Asia

Atsushi Tanaka[1] **Yoshinori Sanada**[2] **Yasuhiro Yamada**[2] **Toshifumi Matsuoka**[2] **Yuzuru Ashida**[2]

Key Words: tectonics, analogue experiment, numerical simulation, discrete element method

ABSTRACT

Analogue physical modelling using granular materials (i.e., sandbox experiments) has been applied with great success to a number of geological problems at various scales. Such physical experiments can also be simulated numerically with the Discrete Element Method (DEM). In this study, we apply the DEM simulation to the collision between the Indian subcontinent and the Eurasian Plate, one of the most significant current tectonic processes in the Earth.

DEM simulation has been applied to various kinds of dynamic modelling, not only in structural geology but also in soil mechanics, rock mechanics, and the like. As the target of the investigation is assumed to be an assembly of many tiny particles, DEM simulation makes it possible to treat an object with large and discontinuous deformations. However, in DEM simulations, we often encounter difficulties when we examine the validity of the input parameters, since little is known about the relationship between the input parameters for each particle and the properties of the whole assembly. Therefore, in our previous studies (Yamada et al., 2002a, 2002b, 2002c), we were obliged to tune the input parameters by trial and error.

To overcome these difficulties, we introduce a numerical biaxial test with the DEM simulation. Using the results of this numerical test, we examine the validity of the input parameters used in the collision model. The resulting collision model is quite similar to the real deformation observed in eastern Asia, and compares well with GPS data and in-situ stress data in eastern Asia.

INTRODUCTION

Analogue physical experiments are excellent for reproducing earth-process phenomena in the laboratory, and have been implemented for a century. For example, to investigate geodynamic processes in the upper, brittle crust, such experiments have usually been carried out using granular material such as dry quartz sand. The knowledge and information derived from such 'sandbox' experiments forms the backbone of contemporary structural geology. Such experiments now can also be carried out using DEM simulation, a numerical simulation technique that is based on the dynamics of small particles. In a DEM simulation we can select initial properties for each particle more flexibly than with analogue sandbox experiments. We believe that DEM simulations can supplement the role of the sandbox experiment and, at least partly, replace it. Using both analogue and numerical techniques, we can consider the principles and parameters that control geodynamic processes.

In this study, DEM simulation is applied to the Indian collision with Eurasia, one of the largest geodynamic processes in the Earth in scale. An understanding of this collision is essential to the understanding of geological structures in eastern Asia.

COLLISION OF INDIA WITH EURASIA

According to plate tectonics theory, the Indian subcontinent was located at the centre of the Indian Ocean at the end of the Cretaceous, moving northward at a speed of about 10 cm per year, and is thought to have collided with the Eurasian continent in the first half of the Tertiary. Although its speed was reduced by half after the collision, the Indian subcontinent has continued to move northward.

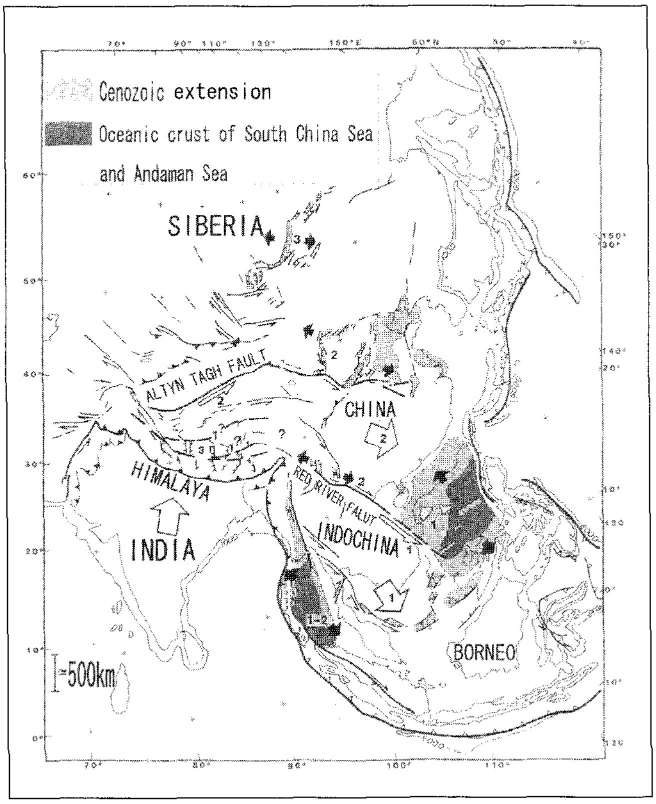

Fig. 1. Deformation of eastern Asia due to the Indian collision (modified from Tapponnier et al., 1982). Heavy lines are major faults or plate boundaries. Open barbs show subduction of oceanic crust. Solid barbs are large intercontinental thrusts. Large open arrows represent qualitatively major block motions with respect to Siberia since Eocene. Smaller solid arrows indicate directions of extension. Numbers near all arrows refer to successive tectonic regimes: 1, Middle Cenozoic; 2, Late Cenozoic.

[1] *Sumiko Consultants Co., Ltd.*
9-7, 2-chome, Ikenohata, Taito-ku,
Tokyo, Japan, 110-0008
Phone: 81-3-3827-6137
Facsimile: 81-3-3827-6147
Email: tanaka.atsushi@sumicon.co.jp

[2] *Department of Civil and Earth Resources Engineering, Kyoto University*
Faculty of Engineering.
Yoshidahonmachi, Sakyo-ku,
Kyoto, Japan, 606-8501

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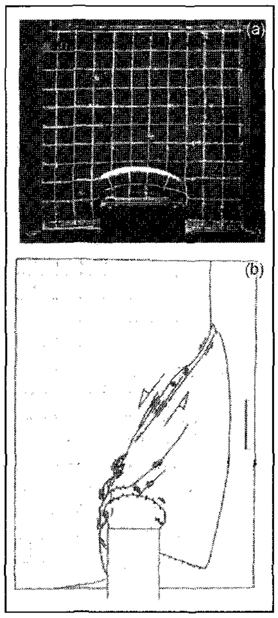

Fig. 2. Analogue model using *combination of dry quartz* sand and silicone polymer (modified from Davy and Cobbold, 1988). a) Picture of the experimental equipment. b) Sketch of one of the experimental results.

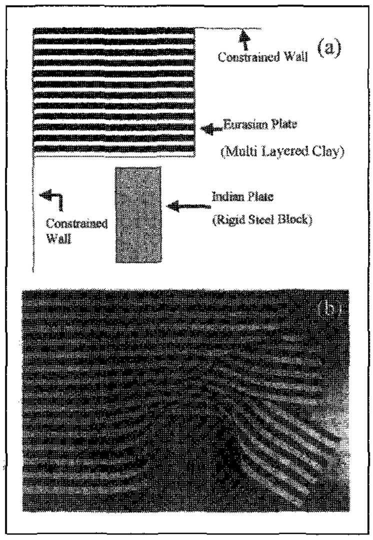

Fig. 3. Analogue model using multi-layered clay (modified from Pelzer and Tapponnier, 1988). a) Sketch of the experiment. b) Image of one of the experimental results.

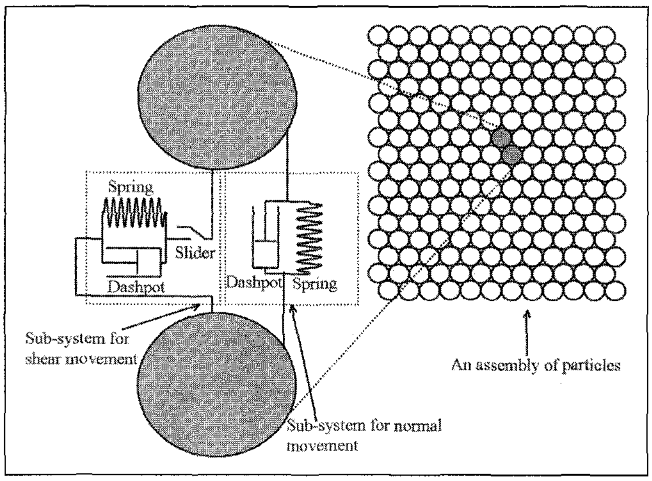

Fig. 4. Spring-dashpot-slider system. There are two sub-systems, one for normal movement, and the other for shear movement. Slider is only for shear movement and ensures that shear force is less than maximum Coulomb friction at the contact.

The collision of the Indian subcontinent with the Eurasian plate is one of the most spectacular current tectonic events on Earth (Figure 1). In order to investigate the associated lithospheric deformation processes, several physical experiments on the collision tectonics have been conducted using analogue materials, such as combinations of dry quartz sand and silicone polymer (Davy and Cobbold, 1988; Figure 2), and layered plasticine (Tapponnier et al., 1982, 1986; Peltzer and Tapponnier, 1988; Figure 3).

Basic assumptions in these experiments included: (1) rigid Indian continent, (2) deformable Eurasian Plate, (3) constrained northern and western margins of the experimental volume, and (4) unconstrained southern and eastern margins. The results of these experiments suggested that such simple tectonic models could explain the major tectonic features in eastern Asia.

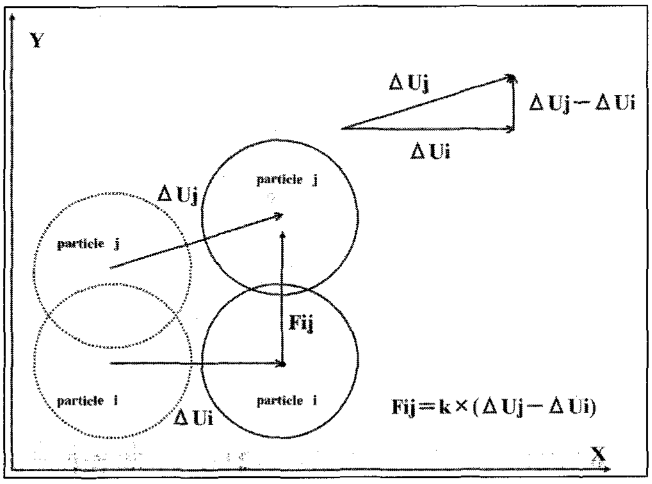

Fig. 5. The interactive force between particle i and particle j. Fij is the interactive force on particle i by particle j; ΔUi is the displacement of particle i; ΔUj is the displacement of particle j.

Discrete Element Method simulation

Cundall et al. (1979) originally proposed DEM simulation as a numerical simulation technique in which various kinds of engineering problem could be solved by modelling them as an assembly of tiny particles. The motion of each particle follows Newton's equation of motion, and interactive forces between the particles are described by a spring-dashpot-slider system connecting those particles (Figure 4).

With DEM simulation, we can solve engineering problems that include large-scale deformation and discontinuities, which cannot be solved with conventional continuum-based methods, such as the Finite Element Method, or the Boundary Element Method.

There are two steps in each calculation cycle: the first step is to evaluate interaction forces on every particle, and the second step is to move those particles by numerically integrating Newton's equation of motion for each particle, subject to the given external forces (Matsuoka et al., 2001b). The interaction forces can be evaluated from the force-displacement relationship (Figure 5). The algorithm employed in this study is based on that described briefly by Matsuoka et al. (2001a), and further developed since then.

One of the most important points of a DEM simulation, compared with an analogue physical experiment, is that some data can be extracted from each particle during deformation, such as displacement path (velocity) and stress fields. Displacement or velocity data, and interaction force data, for each particle at every single time step can easily be extracted, since these data sets are produced sequentially during the forward calculation in the time domain.

In order to compute stress-field data for each particle, we introduce the average Cauchy stress tensor, which is defined within the volume V of the deformed configuration as

$$\sigma_{ij} = \left(\frac{1}{V}\right)\sum_{p=1}^{N}\left\{\sum_{p=1}^{M_p} N_{ic}F_{jc}\right\}, \qquad (1)$$

where $\mathbf{N}_{ic}$ is the unit normal at contact c of particle p, $\mathbf{F}_{jc}$ is the contact force at contact c of particle p, N is the number of particles in volume V, and M_p is the number of contacts on particle p (Cundall and Strack, 1983). In this study, this equation is applied to each particle.

SIMULATION RESULTS

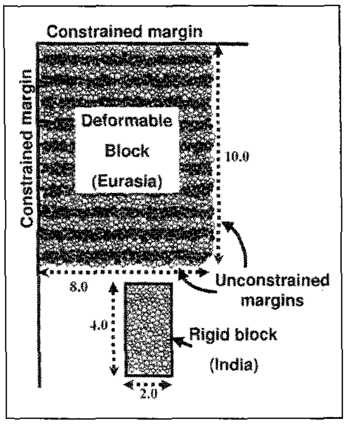

Fig. 6. Sketch of initial geometry in our DEM simulation.

In our previous studies (Yamada et al., 2002a, 2002b, 2002c), we conducted several two-dimensional DEM simulations with the same assumptions as those of the analogue experiments (Figure 6), to examine the effect of choice of input parameters, including the relative position of the indenter (corresponding to India) and the bonding conditions between the particles. In all simulations, the particle size was randomised in a range between 0.06 and 0.14 (dimensionless length) to avoid potential weak planes arising from a 'perfect' initial packing arrangement of uniform-sized particles.

In this study, we conduct several DEM simulations to examine the input parameters for particle interaction, such as bonding radius and viscous coefficient. Figure 7a shows a simulation result for conditions of homogeneous mild bonding and high viscosity. The collision produced progressive development of fault systems, expressed as lines of gaps between the particles, which propagated from the left corner of the indenter to the unconstrained right margin. The boundary at the right side of the particle assembly is broadened in response to the space problem arising in the collision.

The DEM simulation result mentioned above is similar to that of the analogue modelling conducted by Tapponnier et al. (1982, 1986), and is also similar to the observed deformation of eastern Asia, which is mainly controlled by the development of two major faults (Red River Fault and Altyn Tagh Fault; Figure 1).

During the deformation, the velocity of, and stresses on, each particle were also extracted and their variations with time were examined. Figure 7b shows the velocity distribution of the particles at the same time step as Figure 7a. The pattern suggests that the collision pushed a small continental fragment to the east. The velocity was calculated for a short time period, and the pattern shown changed immediately after this scene. The velocity pattern sometimes shows a series of 'explosion' features which correspond to slip events along faults.

Figure 7c shows normal stress fields on each particle. These vectors correspond to the stress by which each particle will move in the next time interval. The directions are generally toward the fixed end walls and perpendicular to fault surfaces where they exist. These vectors are also unstable and change in direction where slip events occur along faults. The shear stress fields are presented in Figure 7d. The white particles are rotating in a counter-clockwise direction, whereas the black ones are rotating in a clockwise direction. Several regions of white particles can be seen in front of the indenter, simulating left-lateral fault zones. A continental block to the right of the indenter has been fragmented, and has rotated in a clockwise direction.

Comparison with Experiments, GPS, and In-situ Stress Fields

The plasticine models by Tapponnier et al. (1982, 1986) are characterized by sequential development of major fault systems and rotation of fragmented continental blocks (Figure 3). Davy and Cobbold (1988) constructed analogue models that were properly scaled to lithospheric deformation, and found that formation of a single major shear zone was the common feature in this tectonic setting (Figure 2). In our previous studies (Yamada et al., 2002a, 2002b, 2002c) and in this study, the DEM simulation produced both types of faulting with similar geometry: initiation at the left corner of the indenter and propagation to the right margin of the particle assembly. This suggests that the input parameters that we used are major factors in controlling deformation style. Immediately in front of the indenter, thrust faults perpendicular to the indentation were produced in the physical experiment (Figure 3), and the layers were thinned in the corresponding position in the DEM simulation (Figure 7a).

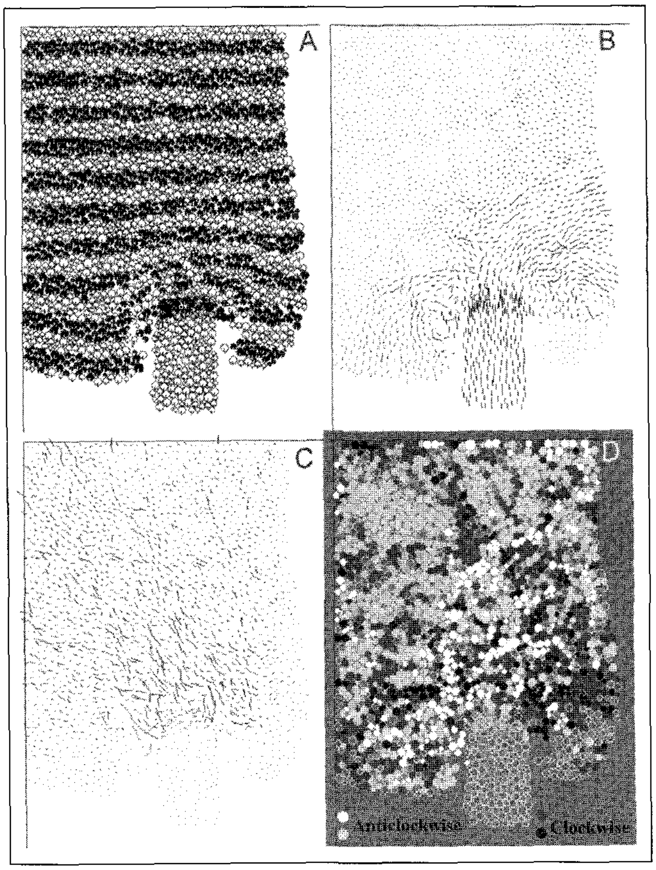

Fig. 7. DEM simulation results, at one instant during deformation. a) Deformation Geometry. b) Velocity distribution. c) Normal stress. d) Shear stress. Light symbols denote particles that are rotating anticlockwise; dark symbols denote particles that are rotating clockwise.

Features of the DEM simulation results that differ from the analogue experiments are related to the larger size of the particles in the DEM simulation, which significantly affects the resolution of deformation structures.

The velocity distribution in the DEM simulation is equivalent to that in GPS data from studies of the real deformation in eastern Asia. The velocity pattern of the simulation generally shows continuous curvature from the collision front but is commonly affected by faulting (Figure 7b). Such a pattern is quite similar to that suggested by the GPS data (Figure 8), in which the vectors are more smoothly continuous from the Himalayan Mountains.

It is difficult to obtain precise vectors for current stress fields, and only the directions of the maximum horizontal compressive stresses are available (Figure 9). These data can be compared with the normal stress directions in DEM simulation (Figure 7c). The present direction of the maximum horizontal compressive stress

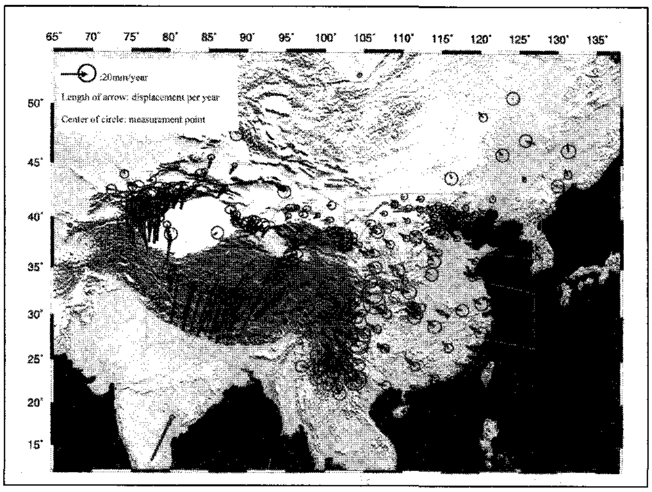

Fig. 8. Present-day motion of eastern Asia suggested by GPS data (modified from Wang et al., 2001).

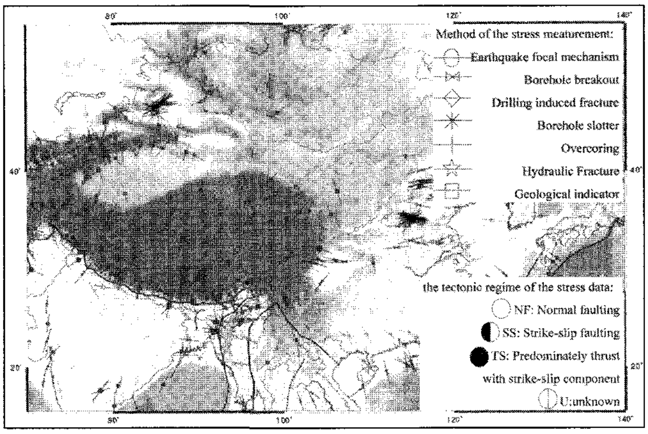

Fig. 9. In-situ stress fields (modified from Mueller et al., 2000).

axis (Figure 9) is generally sub-parallel to direction vectors in the GPS data (Figure 8), suggesting that such large-scale tectonics may be controlled primarily by ductile deformation of the lower crust and its substrate. In the DEM simulation, the directions of the normal stress are generally toward the fixed end walls (Figure 7c), suggesting that this boundary condition, assumed by Tapponnier et al. (1982), may not be appropriate to model the dynamics of the collision process.

NUMERICAL BIAXIAL TEST WITH DEM SIMULATION

In DEM simulation of tectonic processes, little is known about the relationship between the input parameters for each particle ('micro-properties'), and the properties of the whole assembly ('macro-properties'). Therefore, in our previous studies (Yamada et al., 2002a, 2002b, 2002c), we had no other choice but to select values for the input parameters by trial and error.

In this study, we introduce a DEM simulation of the biaxial test, in order to estimate the properties of test pieces, such as Young's modulus, unconfined compressive strength (UCS), and cohesion, with the input parameters for the Indian collision model. In this way, we can tune the input parameters of the collision model so that the properties of the test pieces are similar to those of upper crust.

Figure 10 is a diagram of the numerical biaxial test (rectangular solid model). Walls are placed on the upper and lower surfaces of a test piece. The upper wall moves downward, and the lower wall moves upward at the same speed. These movements apply compressive stress to the test piece. An unconfined test and several confined tests can be simulated to derive the 'macro-properties' of a test piece. In a confined test, constraining forces are applied to the outside particles as the upper and lower walls are moved, but no such force is applied in the unconfined test.

Radius of Particles (m)	0.06–0.14
Density of Particles (kg/m^3)	3000
Bonding Radius	1.01 × (Radius of Particles)
Spring Stiffness (normal)	2.0×10^9
Spring Stiffness (shear)	2.0×10^9

Table 1. Input parameters for particle interaction in a simulated biaxial compression test.

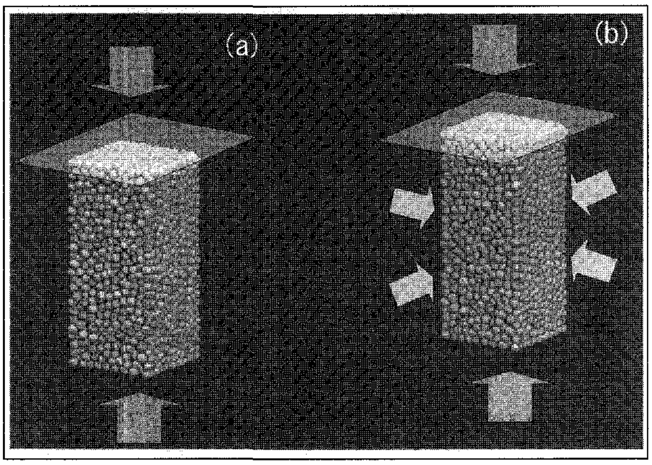

Fig. 10. Sketch of the numerical biaxial test. a) Unconfined test. b) Confined test.

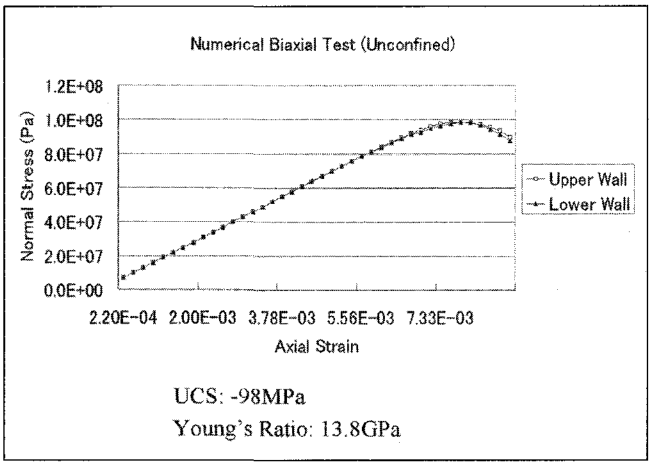

Fig. 11. Stress-strain plot from a simulated unconfined biaxial test.

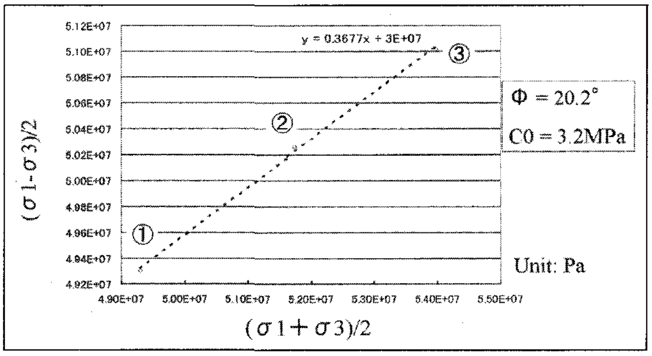

Fig. 12. Linear regression through peak strength data from simulated biaxial tests.

We show the results of numerical biaxial tests with the input parameters shown in Table 1, which are the same as that of the collision simulation (except for particle radii). Figure 11 shows the relationship between stress and strain in the simulated unconfined test. The estimated Young's modulus is 13.8 GPa and the UCS is 98 MPa. Table 2 shows the relationship between peak strength and stress on the outside particles at fracture, in an unconfined test and two confined tests. Figure 12 shows a linear regression through the peak strength data. The estimated internal friction angle is 20.2°, and the cohesion is 3.2 MPa. These estimates are generally similar to those observed in the upper crust.

The results of our DEM simulation of biaxial tests suggest that the spring stiffness and bonding radius parameters mainly determine Young's modulus and UCS for the assembly. However, the factors that determine the internal friction angle and the cohesion of a whole assembly are still controversial.

Test	σ_1 (Pa)	σ_3 (Pa)
1 : Unconfined	9.86 × 107	0
2 : Confined	1.02 × 108	1.48 × 106
3 : Confined	1.05 × 108	2.96 × 106

Table 2. Peak stress data from simulated confined/unconfined biaxial tests (3 cases).

CONCLUSIONS

DEM simulation results can be correlated with scaled physical experiments carried out under similar boundary conditions, and with observations of natural deformation, including GPS velocity data and in-situ stress data. Therefore, the method is a powerful tool with which to analyse natural geological deformations, to validate quantitatively the parameters that control deformation, and to construct dynamic models of structural deformation development in time and space.

The stress fields and velocity distributions extracted from our DEM simulations, with a condition of homogeneous bonding and high viscosity, are relatively stable and smooth compared with other results in our previous studies (Yamada et al., 2002a, 2002b, 2002c). In addition, the deformation geometry is similar to the experimental results of Tapponnier et al. (1982, 1986) and to observed deformation in eastern Asia. Therefore, the actual collision of the Indian subcontinent with the Eurasian plate may be controlled mainly by ductile deformation of the lower crust and its substrate, and the stress field in the upper crust vary in response.

In addition, we have introduced the numerical biaxial test in this study, to help us to estimate the validity of the input parameters for particle interaction. The result of DEM simulation of the collision, with input parameters selected on the basis of results from numerical biaxial testing, is similar to the actual deformation in eastern Asia, and compares well with GPS and in-situ stress data. It demonstrates that the combination of the collision-simulating model and numerical biaxial testing gives us the best way to study the geodynamic principles and parameters that control tectonic deformation.

REFERENCES

Cundall, P.A., and Strack, O.D.L., 1979, A discrete numerical model for granular assemblies, A self-consistent mechanics of composite materials: *Geotechnique*, **29**, 47–65.

Cundall, P.A., and Strack, O.D.L., 1983, Modeling of microscopic mechanisms in granular material: in *Mechanics of granular materials: new models and constitutive relations*, Jenkins, J.T., and Satake, M., (eds.), Elsevier, 137–149.

Davy, P., and Cobbold, P.R., 1988, Indentation tectonics in nature and experiment. 1. Experiments scaled for gravity: *Bulletin of the Geological Institutions of Uppsala, N. S.*, **14**, 129–141.

Matsuoka, T., Hasegawa, T., Yamada, Y., and Ashida, Y., 2001a, Analogue and digital modeling in structural geology: *Proceedings of the Recent Advances in Exploration Geophysics*, Kyoto, Japan.

Matsuoka, T., Hasegawa, T., Yamada, Y., and Ashida, Y., 2001b, Computer simulation for sandbox experiments: *Extended abstract of the Annual meeting, the Society of Exploration Geophysicists*, San Antonio, TX, USA.

Mueller, T., Reinecker, J., Heidbach, O., and Fuchs, K., 2000, *The 2000 release of the World Stress Map: World Stress Map Project.* [Web document]: Accessed 20 December, 2004. Available at <http://www.world-stress-map.org>.

Peltzer, G. and Tapponnier, P., 1988, Formation and evolution of strike-slip faults, rifts, and basins during the India-Asia collision: an experimental approach: *Journal of Geophysical Research*, **93**, B12, 15085–15117.

Tapponnier, P., Peltzer, G., Armijo, R., Le Dain, A.Y. and Cobbold, P., 1982, Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine: *Geology*, **10**, 611–616.

Tapponnier, P., Peltzer, G., and Armijo, R., 1986, On the mechanics of the collision between India and Asia, propagating extrusion tectonics in Asia: in *Collision Tectonics*, Coward, M.P., and Ries, A.C. (eds.), Geological Society Special Publication, **19**, 115–157.

Yamada, Y., Tanaka, A., and Matsuoka, T., 2002a, DEM Simulation of Indentation Tectonics: Continental Collision of Indo-Eurasia: *Proceedings of the Recent Advances in Exploration Geophysics*, Kyoto, Japan.

Yamada, Y., Tanaka, A., and Matsuoka, T., 2002b, DEM simulation of continental collision; Insights for indentation tectonics in Asia: *Bollettino di Geofisica teorica et applicata*, **42**, 1/2 supplement, 245–249.

Yamada, Y., Atsushi, T., and Matsuoka, T., 2002c, DEM Simulation of Continental Collision in Asia: *Abstract of the Fall Meeting, the American Geophysical Union*, San Francisco, CA, USA.

Wang, Q., Zhang, P. Z., Freymueller, J, T., Bilham, R., Larson, K, M., Lai, X., You, X., Niu, Z., Wu, J., Li, Y., Liu, J., Yang, Z., Chen, Q., 2001, Present Day Crustal Deformation in China constrained by Global Positioning Measurements: *Science*, **294**, 574–577.

アジアにおける大陸衝突の個別要素シミュレーション

田中篤史 [1]・真田佳典[2]・山田泰広[2]・松岡俊文[2]・芦田 讓[2]

要　旨：　地球科学の分野において、アナログモデル実験は地球上に存在する物質との間に何らかの類似性を持つ物質を用いて、地球科学現象を実際の時間や長さなどを縮小して実験室内で等価に再現することができる優れた手法である。実験材料として乾燥砂を用いたアナログモデル実験(砂箱実験)は、上部地殻の脆性的な変形挙動を近似できることから、上部地殻における地質構造形成過程を再現するための優れたツールとして広く用いられている。

本研究では、このアナログモデル実験の境界条件や材料物性などに更なる自由度を与えるために、数値シミュレーション手法の一つである個別要素法(Discrete Element Method ; DEM)を用いた地質構造形成過程を再現するためのデジタルシミュレータを開発した。そして実際の地質モデルとして現在地球上で観察される最もダイナミックな地質現象の一つであるインドーユーラシア衝突を取り上げ、開発したシミュレータを適用し検討を行った。

個別要素法とは力学的挙動に関する数値シミュレーション手法の一つであり、解析対象を微小な粒子の集合体として近似する手法で、不連続性や大変形を伴う対象の解析に適している。本研究のように地質モデルに適用されるだけでなく、岩盤力学や土質力学など幅広い分野で適用されている。

しかし、個別要素法における各個別要素に設定するパラメータと解析対象全体の物性との関係において不明なところが多く、これまで多くの場合、解析対象全体の挙動が妥当なものになるように試行錯誤 (trial and error) によって入力パラメータのフィッティングを行い、解析が行われてきた。そのため、得られた解析結果が唯一解であるか否かという検証を行うことが困難である。

本研究では個別要素法を用いた圧縮試験のシミュレータも同時に開発した。そして、インドーユーラシア衝突モデルのシミュレーションで用いたパラメータを入力し圧縮試験を行い、供試体の物性を調べることで実際の衝突・侵入の過程に関する考察を行った。

아시아 대륙충돌의 개별요소 시뮬레이션

Atsushi Tanaka [1]・Yoshinori Sanada[2]・Yasuhiro Yamada[2]・Toshifumi Matsuoka[2]・Yuzuru Ashida[2]

요　약:　조립질 물질을 이용한 축소모형실험(예를 들어 모래상자실험)은 다양한 크기의 많은 지질학적 문제에 성공적으로 적용되어왔다. 이러한 물리적 실험은 개별요소법(DEM)을 이용하여 수치적으로도 수행될 수 있다. 이 연구에서는 현재 지구상에서 가장 중요한 지구조적 과정 중의 하나인 인도판과 유라시아판의 충돌문제를 시뮬레이션하기 위해 개별요소법을 적용하였다.

개별요소 시뮬레이션은 구조지질학뿐만 아니라 토질역학, 암석역학 등의 다양한 동역학적 분야에 적용되어왔다. 조사대상이 많은 작은 입자들의 조합으로 가정되기 때문에 개별요소 시뮬레이션은 거대하고 불연속적인 변형이 일어나는 대상을 다룰 수 있다. 그러나 DEM 시뮬레이션에서는 개개 입자에 대한 입력변수들과 전체 물성의 관계에 대해 거의 알려져 있지 않기 때문에 입력 변수들의 타당성을 검증하기 어려운 경우가 자주 있다. 그러므로 이전의 연구들에서는 시행착오에 의해 입력변수를 조정하여만 하였다.

이러한 어려움을 극복하기 위하여, 이 연구에서는 개별요소 시뮬레이션에 수치적인 이축 시험을 도입하였으며, 이러한 수치 시험 결과를 이용하여 충돌 모델에 사용되는 입력변수의 타당성을 검토하였다. 결과적인 충돌 모델은 동아시아에서 관측되는 실제 변형과 매우 비슷하며, GPS 자료 및 동 아시아의 원위치 응력자료와 잘 대비된다.

1 住鉱コンサルタント(株) 技術開発部
〒110-0008　東京都台東区池之端2丁目9-7
2 京都大学大学院工学研究科 社会基盤工学専攻

1 주광컨설턴트(주) 기술개발부
2 쿄토대학대학원공학연구과 사회기반공학전공