行政院國家科學委員會補助專題研究計畫成果報告

台灣及鄰近地區地殼變形之數值研究模式(III)：
應力軸轉換之三維數值模式分析

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計畫主持人：胡植慶
共同主持人：朱傚祖
計畫參與人員：李建成

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計畫參與人員：李建成　中央研究院地球科學研究所

一、中文摘要

利用三維數值模式分析研究脆性變形中常見之主應力軸交換的現象，在野外量測斷層滑移及地震斷層機制解中常可從逆推的主應力軸方向，觀測到上述之主應力軸交換之現象。本研究之主要目的在於利用三維數值模式建立主應力軸交換的力學模式，至於因間冰期所產生之彈性回跳所造成之主應力軸交換則不在本研究範疇內。

不管遠場的應力狀態，由因岩體流變性質的改變造成應力值的改變足以更改局部的構造應力分布而造成主應力軸交換，此主應力軸交換並不是單純肇因於方向上的改變，而大部分是肇因於主應力值的變化。此結果與自然界之觀察頗為一致。雖然因應力軸方向的改變所造成的主應力軸交換亦存在，但應力值的改變卻是造成主應力σ_1-σ_2 或σ_2-σ_3 軸交換的主要因素，此結果與脆性構造變形的觀察相吻合。值得注意的是本研究的結果是在邊界條件中間主應力值等於最大主應力值及最小主應力值和之平均（Φ值等於 0.5）下完成。一般而言，較低的Φ值較易造成σ_2/ σ_3 軸交換，而較高的Φ值較易造成σ_1/ σ_2 軸交換。

以地質的特性而言，主應力軸交換的主要因素在於脆性變形的異質性（如在斷層密部的地塹變形帶中存在著較剛性的塊體）或是斷層及斷裂作用所造成的力學性質的非均向性（如岩體中平行斷層走向比其他方向更剛性），我們的研究明確顯示力學性質的非均向性易於造成主應力軸交換。因在自然界中變形帶常隨著時間及空間而演變，因此主應力軸交換的現象非常普遍。

關鍵詞：數值模式、脆性變形、應力軸交換

Abstract

Using 3-D distinct-element modeling, we explore a variety of simulations to characterize the stress permutations observed in brittle tectonics. Stress inversions of fault slip data or earthquake focal mechanisms often reveal such permutations. The main aim of our study is to produce mechanically consistent 3-D models that account in a simple way for switches between principal stress axes σ_1-σ_2 or σ_2-σ_3. Other phenomena, such as those related to elastic rebound, are beyond the scope of this work.

It appears that the stress changes induced by variations in rheology are large enough to modify the local tectonic behavior and produce permutations of principal stress axes, despite the simplicity of far-field boundary conditions. Rather than simple directional changes, which exist but are limited, the relative variations in principal stress values are the major cause of permutations σ_1-σ_2 and σ_2-σ_3. This is in good agreement with observations in nature, where despite permutations the orientations of axes often remain tightly clustered. Note that the most demonstrative experiments were done with a ratio Φ of 0.5, implying that σ_2 is the arithmetic mean between σ_1 and σ_3 (low Φ ratios favor σ_2/ σ_3 permutations, whereas high Φ ratios favor σ_1/ σ_2 ones).

In terms of geological significance, we conclude that the major causes of stress permutations are the heterogeneity of the brittle deformation (e.g., intact rock massifs between heavily faulted grabens of deformation zones)

and the anisotropy of the mechanical properties that results from the fracturing and faulting (that is, a rock more resistant in the direction parallel to faults than in other directions). Our modeling effectively revealed that anisotropy in rock properties favor stress permutations. Of major importance seems to be the existence of relatively resistant zones at the tips of deformed ones, acting as channels where stress concentrates and switches occur. Because in nature such zones move in time and space, it is not surprising that stress permutations are so pervasive.

In our modeling experiments, we explored a variety of compressional, extensional and strike-slip tectonic situations involving stress permutations.

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Keywords: 3-D numerical modeling, brittle tectonics, stress permutations

Introduction

Stress permutations are common in brittle tectonics at local and regional scales [*Angelier and Bergerat* 1983; *Angelier et al.,* 1985; *Larroque, et al.,* 1987; *Yeh et al.,* 1991; *Hippolyte et al.,* 1992; *Angelier,* 1994]. While reconstructing paleostress from fault-slip data or principal stress from focal mechanisms, one often identifies several stress tensors recorded in a single site. Some tensors correspond to distinct tectonic events, these events may reflect either polyphase tectonism or block rotation for monpohase tectonism. The other tensors which have common symmetry axes, may result from linked mechanisms which often occurred almost contemporaneously. Such changes in time as well as in space are described as permutations of stress axes [e.g., *Angelier and Bergerat*, 1983; *Letouzey*, 1986]. In most cases, the intermediate principal stress σ_2 is replaced either by maximum compressional stress σ_1 or by the minimum stress σ_3 (permutations σ_1/σ_2 and σ_2/σ_3, respectively). Many variations in stress state are related to rapid stress permutations such as the accommodation of deformation within complex inherited structural patterns, variations in lateral confining pressure and overburden pressure.

As indicated by Barrier and Angelier [1986], the compressional stress axis σ_1 determined in the Costal Range of Eastern Taiwan has average trends of N120^o-130^{o}E and very shallow plunges, whereas the minimum stress axis σ_3 is either close to vertical (reverse faulting regime) or shallow plunging (strike-slip faulting regime). This result confirmed that permutations between σ_2 and σ_3 axes were frequent. They inferred that the tectonic activity in the Longitudinal Valley fault zone is dominated by NW-SE compression that induces reverse faulting with minor left-lateral component. For instance, where extensional faulting occurs, such permutations result either in perpendicular systems of conjugate normal faults (σ_2/σ_3 permutation) or in mixed conjugate sets of normal and strike-slip faults (σ_1/σ_2 permutation). The σ_1/σ_2 permutation in extensional deformation was described by around the Hoover Dam area [*Angelier et al.,* 1985; *Angelier,* 1989] cross-cutting relationships may reveal intricate sequences from normal dip-slip to strike-slip, or from strike-slip to normal dip-slip. Whereas simple extension generally corresponds to relatively high values of Φ (e.g. 0.5), multidirectional extension is characterized by low values that make stress permutation (σ_2/σ_3) easier. A similar effect accounts for reverse/strike-slip changes of faulting mode in compressional deformation: low values of Φ generally correspond to situations characterized by σ_2/ σ_3 permutations. These considerations also highlight the major role played by the ratio between principal stress differences: the importance of reverse/strike-slip mixed modes of faulting increases as Φ decreases in a compressional stress regime. Conversely, a decrease in the ratio Φ in an extensional stress regime results in more irregular trajectories of σ_3 and local permutations of σ_2/ σ_3 fault slip analyses in Crete revealed low values of Φ and frequent permutations between σ_2 and σ_3 axes [*Angelier*, 1994].

In this paper, we aim at characterizing the stress permutations induced by stress field change resulted from the presence of pre-existing discontinuities and mechanical anisotropy of blocks. To address the problem of modeling stress fields around mechanical discontinuities with anisotropic block material, we use a 3-D distinct-element numerical modeling approach. To clearly identify the sources of permutation, we analyze simple geometrical patterns, not complex ones in which large numbers of singularities concur to produce stress perturbations and permutations. For this reason, the relatively minor discontinuities inside fracture zones, which induce additional perturbations in the deformation field, are not taken into account. We consequently restrict our study to simple cases, with few major discontinuities and simple patterns of blocks, so that mechanical constraints can be clearly defined and validated with geological data. We especially consider elongated zones of mechanical weakness with anisotropic properties, a common feature in structural geology. We thus combine a 3-D numerical simulation with the knowledge of the deformation pattern in compressional, extensional and strike-slip tectonic settings, in order to check the mechanical validity of the observed stress permutations. We finally show that although the stress permutation phenomenon certainly adds much to the structural complexity, it obeys relatively simple laws and can be accounted for by simple mechanisms that involve variations in rheology.

Discussion and Conclusion

Even with the simple configuration adopted, the numerical modeling of the stress permutation phenomenon involves a wide range of possible cases, depending on the orientation of the far-field stress (e.g., normal, reverse and strike-slip in type), the principal stress values (e.g., the ratio Φ and the principal stress differences), the relative size of the different domains and the type and degree of anisotropy (e.g., the ratio E'/E). The models shown before simply illustrate few typical cases, from which other responses can be derived. As a major target, we considered the role of the anisotropy in Young's modulus, which aims at reproducing in a simple way the anisotropic distribution of mechanical properties induced by layering, faulting and fissuring. It is known that major sources of stress variations are related to the presence of mechanical discontinuities in the crust. They were not considered in this paper, because we aimed at demonstrating that even in very simple cases, with few homogeneous domains, stress permutations occur very often. One may easily infer that stress permutations must be more frequent in detail, where mechanical discontinuities are present. A recent paper illustrated the importance of such phenomena in the case of an oceanic transform fault in Iceland, showing that a large variety of stress states can be attributed to variations in coupling along a major discontinuity [*Angelier et al.*, 2000]. Such observations can be multiplied in various tectonic settings, and deserve careful consideration because stress deviations and stress permutations were often interpreted in terms of independent tectonic events, although they may simply reflect variations during a single event.

As mentioned above, the intact rocks are not too strongly anisotropic compared to pre-fracturing and pre-faulting rock masses. Our models deal with the intact blocks as isotropic and homogeneous rock masses. However, several authors [e.g., Worotnicki, 1993, Telesnick et al., 1995] have indicated that most intact transversely isotropic rocks, the ratio E/E' approximately varies between 1 to 4. For examples, most of the quartzofeldspathic and basic/lithic rocks show the low to moderate degree of anisotropy with a maximum to minimum Young's modulus ratio E_{max}/E_{min} less than 1.5, for carbonate rocks an intermediate degree of rock anisotropy with E_{max}/E_{min} not exceeding 1.7 [Worotnicki, 1993]. As for the highest degree of anisotropy such as pelitic clay and pelitic mica rocks, this ratio was found with most cases low than 4. If the anisotropic properties really exist inside the intact rock due to the foliation and stratification, the partial stress permutations or additional stress perturbation should be expected. Base on the results of tests of degree of anisotropy, the E/E'= 3.33 seems to be a critical value for the delimitation of significant stress permutations inside the anisotropic blocks due to the pre-existing fracturing in the deformation zone. Being able to account for the directional character of pre-fracturing rock masses, it is suitable for assuming the intact rock mass bounded by two anisotropic blocks to be isotropic, as a fact that the E_{max}/E_{min} ratio varies between 1 and 4 for the above-mentioned rocks.

From a mechanical point of view, one should expect intact rock anisotropy to be stress dependent with a decrease in anisotropy with an increase of stress [Homand et al., 1993]. This phenomenon was observed and conducted by ultrasonic tests on slates during triaxial compression tests at confining pressure up to 40 MPa. It is most likely that pores and microcracks in rock would close under confinement and result in an increase in the overall rock stiffness. In our models, we fix our boundary conditions with stress, so the stress dependency of rock anisotropy is beyond the scope of our study. However, the acceptable predictions of rock behavior can be achieved by assuming anisotropic elasticity as long as the selected rock properties are determined in a stress range comparable to what is expected in different tectonic settings. We conclude that the stress changes induced by variations in rheology are large enough to modify the local tectonic behavior and produce permutations of principal stress axes, despite the simplicity of far-field boundary conditions. Rather than simple directional changes, which exist but are limited, the relative variations in principal stress values are the major cause of permutations σ_1-σ_2 and σ_2-σ_3. This is in good agreement with observations in nature, where despite permutations the orientations of axes often remain tightly clustered. Note that the most demonstrative experiments were done with a ratio Φ of 0.5, implying that σ_2 is the arithmetic mean between σ_1 and σ_3 (low Φ ratios favor $\sigma_2/\ \sigma_3$ permutations, whereas high Φ ratios favor $\sigma_1/\ \sigma_2$ ones). In terms of geological significance, we conclude that the major causes of stress permutations are the heterogeneity of the brittle deformation (e.g., intact rock massifs between heavily faulted grabens of deformation zones) and the anisotropy of the mechanical properties that results from the fracturing and faulting (that is, a rock more resistant in the direction parallel to faults than in other directions). Our modeling effectively revealed that anisotropy in rock properties favor stress permutations. Of major importance seems to be the existence of relatively resistant zones at the tips of deformed ones, acting as channels where stress concentrates and switches occur. Because in nature such zones move in time and space, it is not surprising that stress permutations are so pervasive.

Reference:

Amadei, B., Importance of anisotropy when estimating and measuring in situ stresses in rock, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 33, 293-325, 1996.

Amadei, B., W.Z. Savage, and H.S. Swolfs, Gravitional stresses in anisotropic rock masses, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 24, 5-14, 1987.

Angelier, J., Fault slip analysis and paleostress reconstruction, In *Continental Deformation (Edit by P. Hancock), 53-100,* Pergamon, New York, 1994.

Angelier, J., and F. Bergerat, Système de contrainte en extension intracontinentale, *Bull. Centr. Rech. Expl. Prod. Elf-Aquitaine,* 7, 137-147, 1983.

Angelier, J., B. Colletta, and R.E. Anderson, Neogene paleostress changes in the Basin and Range: a case study at Hoover Dam, Nevada-Arizona, *Bull. Geol. Soc. Am., 96*, 347-361, 1985.

Angelier, J., E. Barrier, and H.-T. Chu, Plate collision and paleostress trajectories in a fold-thrust belt: the Foothills of Taiwan, *Tectonophysics, 125,* 161-178, 1986.

Angelier, J., F. Bergerat, and C. Catherine, Variable coupling across weak oceanic transform fault: Flateyjarskagi, Iceland, *Terra Nova*, 12, 97-101, 2000.

Barrier, E., and J. Angelier, Active collision in eastern Taiwan: the Coastal Range, *Tectonophysics, 125,* 39-72, 1986.

Cundall, P.A., Formulation of a three-dimensional distinct element Model-Part I: a scheme to detect and represent contacts in a system composed of many polyhedral blocks, *Int. J. Rock Mech. Min. Sci. & Geomech. Abs. 25*, 107-116, 1988.

Deschamps, A., and G.C.P. King, Aftershocks of the Campania-Lucania (Italy) Earthquake of 23 November 1980. *Bull. Seism. Soc. Am., 74,* 2483-2517, 1984.

Dupin J.-M., W. Sassi and J. Angelier, Homogeneous stress hypothesis and actual fault slip: a distinct element analysis, *Journ. Struct. Geol., 15,* 1033-1043, 1993.

Harper, T.R. and Last, N.C., 1990. Response of fractured rock subject to fluid injection. Part III. Practical application. *Tectonophysics*, *172*, 53-65.

Hart, R., P.A. Cundall, and J. Lemos, Formulation of a three dimensional distinct element model. Part II. Mechanical calculations for motion and interaction of a system composed of many polyhedral blocks. *Int. J. Rock Mech. Min. Sci. & Geomech. Abs. 25*, 117-125, 1988.

Hippolyte, J.-C., J. Angelier, and F. Roure, Les permutations d'axes de contraintes: exemples dans des terrains quaternaries du Sud de l'Apennin (Italie), *C. R. Acad. Sci.*

Paris, 315, 89-95, 1992.

Homberg, C., J.-C. Hu, J. Angelier, F. Bergerat, and O. Lacombe, Paleostress deviations around major fault zones: a case study in the Jura Mountains. *Journ. Struct. Geol.*, *19*, 703-718, 1997.

Hu, J.-C., J. Angelier, and S.-B. Yu, An interpretation of the active deformation of southern Taiwan based on numerical simulation and GPS studies, *Tectonophysics*, *274*, 145-169, 1997.

Hu, J.-C., S.-B. Yu, J. Angelier, and H.-T. Chu, Active deformation of Taiwan from GPS measurements and numerical simulations, *J. Geophys. Res.*, 106, 2265-2280, 2001.

Hu, J.-C., J. Angelier, C. Homberg, J.-C. Lee, and H.-T. Chu, Three-dimensional modeling of the behavior of the oblique convergent boundary of southeast Taiwan: friction and strain partitioning, Tectonophysics, 333, 261-276, 2001.

King, M.S., M. Andrea, and M. Shams Khanshir, Velocity anisotropy of carboniferous mudstones. *Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr., 31*, 261-263, 1994.

Kwasnieswki, M.A., Mechanical behavior of anisotropic rocks. In *Comprehensive Rock Engineering (Edited by J.A, Hudson), Vol. 1, Chap. 12*, 285-312, Pergamon, Oxford, 1993.

Larroque, J.-M, A. Etchecopar, and H. Philip, Evidence for the permutation of stress σ_1 and σ_2 in the Alpine foreland: the example of the Rhine graben, *Tectonophysics*, *144,* 315-322, 1987.

Letouzey, J., Cenozoic paleo-stress pattern in the Alpine Forland and structural interpretation in a platform basin, *Tectonophysics*, *132,* 215-231, 1986.

Last, N.C., and T.R. Harper, Response of fractured rock subject to fluid injection Part I: Development of a numerical model, *Tectonophysics*, *172*, 1-31, 1990.

Martin, C.D., and G.R. Simmons, The Atomic Energy of Canada Limited Underground Research Laboratory: an overview of geomechanics characterization. In *Comprehensive Rock Engineering (Edited by J.A. Hudson), Vol. 3, Chap. 38,* 915-950, Pergamon, Oxford, 1993.

Mercier J.-L., R. Armijo, P. Tapponnier, E. Carey-Gailhardis, and H.-T. Lin, Change from late Tertiary compression to Quaternary extension in southern Tibet during the India-Asia collision, *Tectonics, 6*, 275-304, 1987.

Mercier, J.-L., and E. Carey-Gailhardis, Regional state of stress and characteristic fault kinematics instabilities shown by aftershocks sequences: the aftershock sequences of the 1978 Thessaloniki (Greece) and Campania-Lucania (Italia) earthquakes as examples, *Earth Planet. Sci. Lett., 92*, 247-264.

Rocher, M., O. Lacombe, J. Angelier, and H.-W. Chen, Mechanical twin sets in calcite as markers of recent collisional events in a fold-and-thrust belt: Evidence from the reefal limestones of southwestern Taiwan, *Tectonics*, *15*, 984-996, 1996.

Ramsay, J.G., and R. Lisle, The techniques of modern structural geology, Vol. 3: Applications of continuum mechanics in structural geology. Academic Press, 2000.

Sassi, W., B. Colletta, P. Balé, and T. Paquereau, Modelling of structural complexity in sedimentary basins: the role of pre-existing faults in thrust tectonics, *Tectonophysics*, *226,* 97-112, 1993.

Worotnicki, G., CSIRO triaxial stress measurement cell. In *Comprehensive Rock Engineering (Edited by J.A. Hudson), Vol. 3, Chap. 13*, 329-394, Pergamon, Oxford, 1993.

Yeh, Y.-H., E. Barrier, C.-H. Lin, and J. Angelier, Stress tensor analysis in the Taiwan area from focal mechanisms of earthquakes, *Tectonophysics*, *200,* 267-280, 1991.