Article ID: 1000-9116(2005)05-0544-08

Study on in-situ stress measurement around coastal marginal land in Fujian*

LI Hong (李 宏) AN Qi-mei (安其美) XIE Fu-ren (谢富仁)

Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, *China*

Abstract

The in-situ hydraulic fracturing stress measurements have been carried out around the coastal marginal land in Fujian Province. And the characteristics of magnitude, direction and distribution of tectonic stress have been obtained. Based on the observed stress data, the characteristics and activities of fault zones are analyzed and studied in the paper according to the Coulomb friction criteria. ① The maximum horizontal principal compressive stress is in the NW-WNW direction from the north to the south along the coastline verge, which is parallel to the strike of the NW-trending fault zone, consistent with the direction of principal compressive stress obtained from geological structure and across-fault deformation data, and different from that reflected by focal mechanism solution by about 20°. ② The horizontal principal stress increases with depth, the relation among three stresses is $S_H>S_v>S_h$ or $S_H \approx S_v>S_h$, and the stress state is liable to normal fault and strike-slip fault activities. ③ According to Coulomb friction criteria and taking the friction strength μ as 0.6~1.0 for analysis, the stress state reaching or exceeding the threshold for normal-fault frictional sliding near the fault implies that the current tectonic activity in the measuring area is mainly normal faulting. ④ The force source of current tectonic stress field comes mainly from the westward and northwestward horizontal extrusions from the Pacific and Philippine Plates respectively to the Eurasian Plate.

Key words: **Fujian coast; active fault zone; hydraulic fracturing stress measurement; Coulomb friction criteria**
CLC number: P553 **Document code**: A

Introduction

The southeast coastal margin of Chinese mainland is important to understand the mutual movement, matter exchange and energy transfer between ocean and land lithospheres, as well as their effects. The coastal area in Fujian Province is advanced in economy development but it has frequent earthquakes, or even strong earthquakes. Therefore, the current study on in-situ stress state measurement is of great significance for studying continental dynamics, marginal sea dynamics, seismology, and earthquake prevention and disaster reduction.

The hydraulic fracturing technique was introduced in 1948 from America for the purpose to increase oil and gas production. The theoretical study have been carried out by assuming that rock behavior is taken as a homogeneous, isotropic, elastic, continuous medium and that fluid is impermeable into the well (Hubbert and Willis, 1957). Through the researches in the past decades, the hydraulic fracturing technique has become an effective method for deep in-situ stress measurement.

* **Received date**: 2005-02-01; **revised date**: 2005-05-30; **accepted date**: 2005-06-07.
Foundation item: National Development and Reform Commission [2004]1138.
Contribution No. 2005A012, Institute of Crustal Dynamics, China Earthquake Administration.
E-mail of the first author: lhstress@sohu.com

The measurement of current tectonic stress state has been carried out by the hydraulic fracturing technique in the coastal marginal land of Fujian Province. The results indicate that the maximum horizontal principal compressive stress is in the NW-WNW direction, which is almost parallel to the northwest-trending fault zone and perpendicular to the northeast-trending fault zone. The force source of tectonic stress comes mainly from the westward and northwestward horizontal extrusions from the Pacific and Philippine Plates respectively to the Eurasian Plate. The fault zone activity has been studied with the stress data according to Coulomb friction criteria. The result shows that the relation among the three principal stresses is $S_H>S_v>S_h$ or $S_H\approx S_v>S_h$ and the stress state is liable to normal fault and strike-slip fault activities, which is consistent with the normal fault activity obtained from the geological data.

1 Characteristics of geologic formation

There are two sets of NNE-NE and NW-NNW-trending fault systems in the measuring area, which have formed the primary tectonic pattern in the southeast coastal area (Figure 1). The NW-NNW-trending faults extend mainly along the direction of 320°. From the northeast to the southwest, there are Guanqian-Sandu'ao fault zone, Shunchang-Fuqing fault zone, Yong'an-Jinjiang fault zone and Shanghang-Zhao'an fault zone. These faults have been active since Epipleistocene and parts of them are Holocene active faults with an activity pattern dominated by tensile normal faulting. The NNE-NE-trending active faults are relatively large in scale and strong in activity. Most of them are ultracrustal and right-lateral shear slip faults that control the Mesozoic and Cenozoic sediment and magmatic activities. The NNE-NE-trending active faults are mainly Zhenghe-Haifeng fault zone, Changle-Zhao'an fault zone and Shaowu-Heyuan fault zone. Most of them are Epipleistocene or Holocene active faults. The NW-NNW-trending fault systems extend along the coast and the adjacent sea area from the north to the south with almost parallel intervals, cutting through the NE-trending fault zones, constraining the formation and development of Quaternary graben basin, and controlling the strike of water systems and distribution of coastal bays. In addition, there are usually volcanoes, hot springs and strong earthquakes at the intersection with NE-trending fault zones (DING *et al*, 1999; CHEN *et al*, 1982).

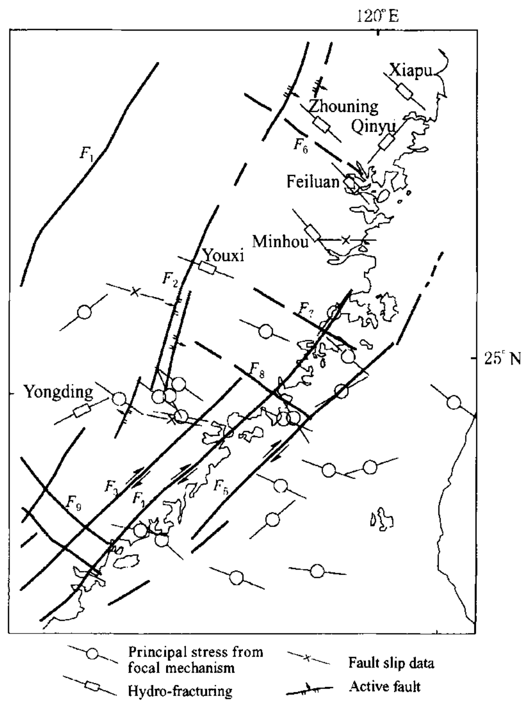

Figure 1 Geological formation and tectonic stress
F_1. Shaowu-Heyuan fault zone; F_2. Zhenghe-Haifeng fault zone; F_3. Fuqingdongzhang-Zhao'andingyang fault zone; F_4. Changle-Zhao'an fault zone; F_5. Niushandao-Xiongdiyu fault zone; F_6. Guanqian-Sandu'ao fault zone; F_7. Shunchang-Fuqing fault zone; F_8. Yong'an-Jinjiang fault zone; F_9. Shanghang-Zhao'an fault zone

2 Results from in-situ stress measurement

2.1 Minbei region

The in-situ stress measurement has been carried out in three boreholes with the depth of about 300~500 m in Zhouning region. The boreholes are located in the east segment of Guanqian-Sandu'ao fault zone. The physiognomy in Zhouning region is medium and small-sized mountains with intermontane basins. The stress measurement is carried out at the location of the above-mentioned mountainous physiognomy with severe denudation. The stratigraphic lithology is flesh-red and milk-white feldspar-granite, which is fresh, intact and hard. The altitudes of the boreholes are 522.73 m, 634.81 m and 588 m with the depths of 340.17 m, 450.20 m and 402.10 m, respectively, and the horizontal distance among them is smaller than 200 m. Furthermore, the depth of boreholes exceeds the range affected by the topography and physiognomy, so the measured results could reflect the deep stress state preferably. The maximum horizontal principal stress denoted by the solid circle is about 12~17 MPa (Figure 2) in the direction of about N42°W (Figure 1), and the minimum one indicated by the open circle is about 10 MPa. The vertical stress is estimated from the lithostatic pressures. As shown in Figure 2, the horizontal principal stress increases with depth.

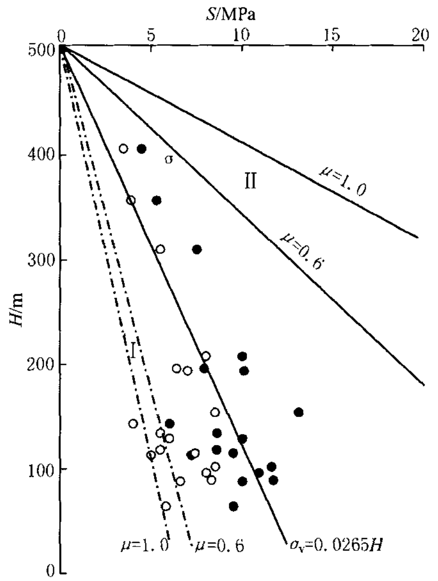

Figure 2 Distribution of stress with depths and critical areas of normal-fault and reverse-fault activities in Zhouning region

I. Critical area of s_h for normal fault activities; II. Critical area of s_H for reverse faulting. Solid circle denotes maximum horizontal stress measured and open circle denotes minimum one. All are the same as those in Figures 3~7

The in-situ stress measurement has been carried out in three boreholes in Ningde-Feiluan region. The boreholes are located at the coastal margin in the east segment of NW-trending Guanqian-Sandu'ao fault zone, neighboring to Shouning-Hua'an NE-trending fault zone. Influenced by the regional tectonic movement, the NW and NE-trending structures intersect each other; faults, dense-fracture zones and structural lines are mainly filled with porphyry. Located in Mindong volcanic eruption zone, the measuring area is composed of the Upper Jurassic acidic volcanic clastic lava and clasolite with a lithology of gray or light-gray liparite tuff. The altitudes of the boreholes are 505.93 m, 208.26 m and 268.26 m with the depths of 429.00 m, 204.01 m and 150.06 m, respectively. The maximum horizontal principal stress is about 10~15 MPa in the direction of about N36°W (Figure 1) and the minimum is about 6~9 MPa. The horizontal principal stress increases with depth as shown in Figure 3.

The in-situ stress measurement has been carried out in four boreholes in Fuding-Xiapu region. The boreholes are located on the south side of NE-trending Fuding-Xiapu fault. Affected by regional tectonic movement, different-directional sublevel faults and dense joint zones have developed in the region with a general direction of NE-ENE. They belong to tension-shear faults and the lithology of boreholes is feldspar-granite. The altitudes of the boreholes are separately 216.32 m, 235.55 m, 227.34 m and 296.69 m, and the depths of the boreholes are respectively 184.88 m, 184.54 m, 184.50 m and 245.50 m. The maximum horizontal principal stress is about 5~13 MPa in the direction of about N48°W (Figure 1), whereas the minimum is about 4~9 MPa. The horizontal principal stress increases with depth as shown in Figure 4.

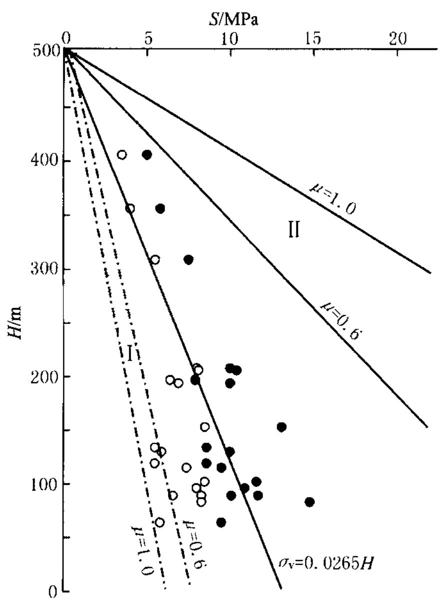

Figure 3 Distribution of stress with depths and critical areas of normal fault and reverse fault activities in Ningde-Feiluan region

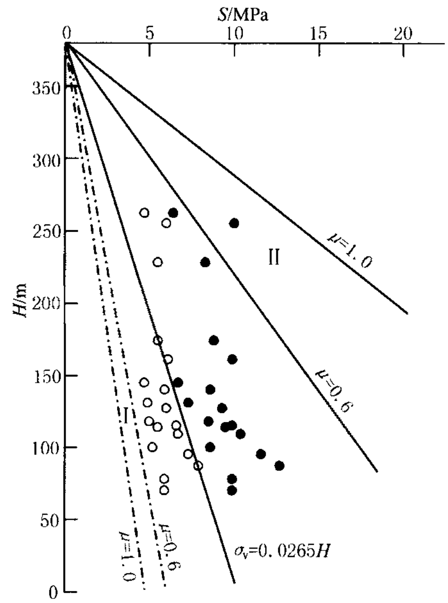

Figure 4 Distribution of stress with depths and critical areas of normal-fault and reverse-fault activities in Fuding-Xiapu region

The in-situ stress measurement has been carried out in two boreholes in Fuding-Qinyu region. The boreholes are located in the SE segment of NE-trending Fuding-Xiapu fault. The representative Liujiang-Qinyu structural zone is a compress-shear fault with a direction of NNE. The lithology of the boreholes is light-gray crystallinoclastic-tuff. The altitudes of the boreholes are 268.58 m and 296.69 m with the depths of 380.57 m and 301.00 m, respectively. The maximum horizontal principal stress is about 5~13 MPa in the direction of about N42°W as shown in Figure 1, while the minimum is about 3~8 MPa. The horizontal principal stress increases with depth (Figure 5).

2.2 Minzhong region

The in-situ stress measurement has been carried out in one borehole in Minhou region. The borehole is located in the north segment of the NNE-trending Changle-Zhao′an fault zone. The principal structure is mainly in the northeast direction, and then the northwest direction. The stratum is mostly the second segment of Upper-series Nanyuan formation of Jurassic and the lithology is tuff lava interlayered with tuff. The altitude of the borehole is 400 m and the depth is 365 m. The maximum horizontal principal stress is about 7~10 MPa in the direction of about N35°W (Figure 1), while the minimum is about 4~7 MPa. The horizontal principal stress increases with depth as shown in Figure 6.

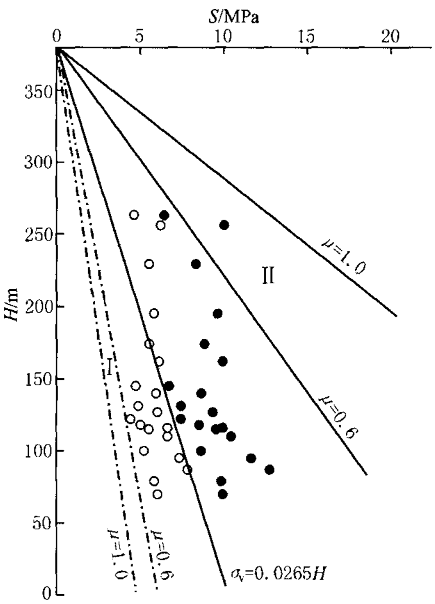

Figure 5 Distribution of stress with depths and critical areas of normal-fault and reverse-fault activities in Fuding-Qinyu region

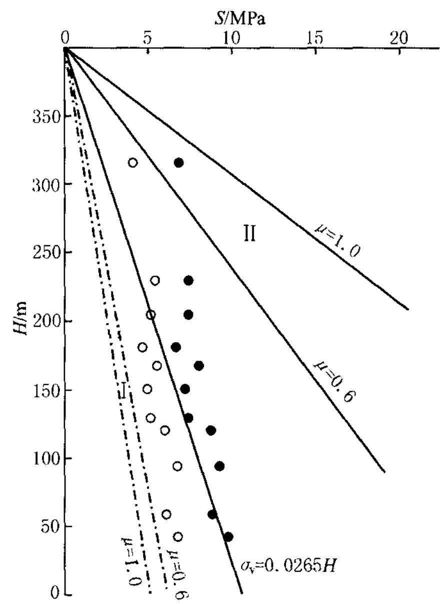

Figure 6 Distribution of stress with depths and critical areas of normal-fault and reverse-fault activities in Minhou region

3 Analysis on in-situ stress state and fault activity around Fujian coastal margin

3.1 In-situ stress state around Fujian coastal margin

Figure 1 shows the distribution of principal compressive stress-axis directions from the measurements in 7 boreholes, fault slip data from 3 measuring sites and principal compressive stress axes of 22 earthquakes around Fujian coastal margin. The principal compressive stress axis is basically in the NW-WNW direction with an approximate "sector" from the shore to the ocean. The result has proved that the tectonic stress affecting the characteristic of neotectonic fracturing around Fujian coastal margin comes mainly from the collision of India block to Chinese mainland and the subduction of Pacific and Philippine Plates along the Okinawa-Taiwan island arc. The principal compressive stress-axis direction obtained from hydraulic fracturing stress measurement is NW, which is 20° different from the WNW direction inferred from the data of fault slip and focal mechanism. From the north to the south, the maximum principal stress axis deflected gradually from the NW to the NWW. Based on across-fault leveling surveys at several sites from 1989 to 2002, HUANG (2003) pointed out that the stress characteristics of the Changle-Zhao'an fault zone are basically the same, *i.e.*, they are compressive reverse faults controlled by the same stress field.

Figure 7 gives the variation of maximum and minimum horizontal principal stresses from Zhouning to Xiapu and Qinyu at the southeastern coastal shore with the altitudes of 260 m and 180 m, respectively. The horizontal principal stress tends to decrease gradually from Zhouning in the northwestern part to Xiapu and Qinyu on the southeast coastal shore with the same altitude.

3.2 Relation among principal stresses and fault activity

Fault activity can be studied according to the fault friction slip criterion. When there exist the relations $S_H>S_h>S_v$, $S_H>S_v>S_h$ and $S_v>S_H>S_h$, it is liable to reverse faulting, strike-slip faulting and normal faulting, respectively.

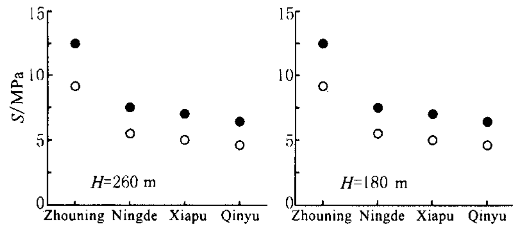

Figure 7 Characteristics of stress distribution from the northwestern part to the southeast coastal shore in Fujian

According to the Coulomb criteria, when the shear stress τ of fault plane is not less than the friction strength $\mu\sigma_n$ of counteraction slip, friction slip would occur along the fault plane. μ is the "friction coefficient" or called "friction strength" defined from the experimental data, σ_n is the normal stress acting on the fault plane. The ratio of maximum to minimum effective principal stresses can be simply expressed as the function of friction coefficient μ. When the fault inherent strength or the cohesion equals to zero, it is given as follows (Jaeger and Cook, 1979):

$$\frac{S_1 - P_0}{S_3 - P_0} = [\sqrt{1+\mu^2} + \mu]^2 \tag{1}$$

Where S_1 and S_3 denote respectively the maximum and minimum principal stresses outside the fault plane, P_0 is the pore pressure, and the intermediate principal stress S_2 is assumed to act on the fault plane. If the ratio of maximum to minimum effective principal stresses is less than the value, the fault is stability; if the ratio were equal to or larger than the value, sliding would occur in the fault with a favorable orientation. The so-called favorable-oriented fault is the one for which the angle between the normal of the fault plane and the orientation of the maximum principal stress S_1 is ϕ, where ϕ is the function of μ given as follows:

$$\phi = \frac{1}{2}\left(\frac{\pi}{2} + \arctan\mu\right) \tag{2}$$

Based on the experimental data of various rocks, Byerlee (1978) suggested that for most rocks μ=0.85 when the stress is less than 100 MPa. LI *et al* (1993) carried out triaxial friction experiment on granite, limestone and sandstone in the Yangtze Gorges area and obtained that the lower limit is $\tau=0.65\sigma_n$, the upper limit is $\tau=1.10\sigma_n$ and the average value is $\tau=0.85\sigma_n$ when the normal stress is less than 150~250 MPa. Zoback suggested that it is reasonable to take the friction coefficient μ as 0.6~1.0 for estimating shallow fault activity (Zoback and Healy, 1984; Zoback and Hickman, 1982).

Figures 2~6 provide the distribution of maximum horizontal principal stress S_H, the minimum horizontal principal stress S_h and the vertical stress S_v estimated from lithostatic pressure with depth in different regions. The corresponding critical areas of horizontal principal stress for normal fault and reverse fault activities are also given, where the pore pressure p_0 is assumed to be equal to the hydrostatic pressure. In Zhouning and Ningde-Feiluan regions, the relation among the three principal stresses is $S_H \approx S_v > S_h$, which is liable to strike-slip and normal fault activities; in Fuding-Xiapu, Qinyu and Minhou regions, the relation among the three principal stresses is $S_H>S_v>S_h$, which is liable to strike-slip fault activity. The possibilities of normal, reverse and strike-slip fault activities are discussed respectively as follows on the basis of the measured stress state and its variation with depth.

1) Normal and reverse faults activities. In general, it is reasonable to estimate vertical stress from lithostatic pressure. The normal faulting would occur when the minimum horizontal principal stress is less than the critical value. As shown in Figures 2~6, the minimum horizontal principal stress observed at the attitude around 100 m has reached the critical area in Zhouning and Ningde-Feiluan regions, and some measuring sites have approached the critical area in other three regions, which illustrates that normal faulting might occur in part of the NW-trending faults around Fujian coastal marginal land. As to the stress states in the five measuring areas, the vertical stress basically equals to the intermediate principal stress or approaches the minimum horizontal principal stress, which is not liable to reverse fault activity. As shown in Figures 2~6, the maximum horizontal principal stress has not entered into or approached the critical area, so reverse faulting is hardly possible to occur around Fujian coastal marginal land.

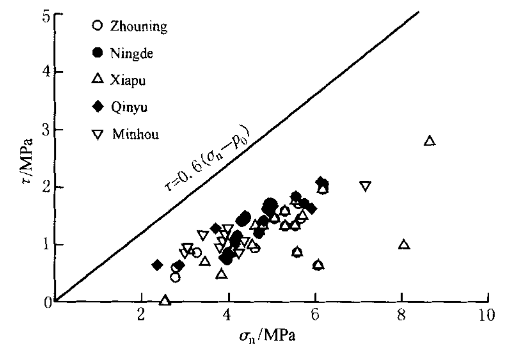

Figure 8 Critical area of strike-slip faults in the coastal marginal shore of Fujian

2) Strike-slip fault activity. The stress state is $S_H>S_v>S_h$ in Fuding-Xiapu, Qinyu and Minhou regions around Fujian coastal marginal shore, which is liable to strike-slip fault activity. We have plotted the stress data measured in the five regions in Figure 8, from which we can see that the measured stress is below the envelope curve, demonstrating that strike-slip faulting would not occur.

4 Discussion and conclusions

1) From the analyses on stress states in the five regions around Fujian costal land and fault activities, we can see that the horizontal tectonic stress is dominant in the tectonic stress field in the shallow crust, the principal stress increases with depth, the principal compressive stress axis is almost perpendicular to the strike of coastline, which is consistent with the direction of major bays. The horizontal stress in northern Fujian is remarkably higher than that in the southeast.

2) The relation of the three principal stresses is $S_H \approx S_v > S_h$ in the northwestern region around Fujian costal land, which is liable to strike-slip and normal fault activities; while the relation of three principal stresses is $S_H>S_v>S_h$ in the southeastern costal land and the central region, which is liable to strike-slip fault activity.

3) According to the Coulomb friction slip criteria, the activity of fault zones around Fujian coasts has been analyzed with the measured stress data. The results illustrate that normal fault activity possibly occurs at the intersection of NNE-trending and NW-trending fault zones, where the local tectonic activity is intensive, the stress state is complex and the stress in a certain segments has reached the critical value for friction slip.

4) In the studied regions, the stress fields in the shallow and deep depths are not consistent completely. In the explanation of fault activity by measured in-situ stress data and seismic study, the correspondence between the near-surface stress data and the deep-seated stress field is significant. Therefore, large amounts of studies have been carried out in this respect both at home and

abroad. It is suggested in general that the measured in-situ stress data should be consistent with the result inferred from the active faults near the measuring sites. For example, based on more than 100 in-situ hydro-fracturing stress measurements in 19 boreholes with the depths of 100~500 m and located along the east boundary of Germany, Rummel (1983) pointed out that both the shallow and deep stress states were constrained by the same tectonic stress field in a stress subregion. XIE *et al* (2004) and LI *et al* (1988) reported the results from their studies that the current tectonic stress field in Chinese mainland has a distinct regional division, and the stress data obtained in the shallow depth in a subregion is consistent with the deep stress state determined by focal mechanism. However, other studies hold that the stress states are not consistent in the shallow crust and the deep seismogenic depth, because the topography and physiognomy are quite complex in shallow depth, the stratum anisotropy is very distinct, the attitude of fault zone might not be invariant along the vertical depth, and the deformation rates of rock strata may be different at different crust depths.

However, the generally accepted viewpoint is that the earthquake development and occurrence is basically a process of energy accumulation and release. From energy variation to triggering earthquake, a series of local small slips would appear on the rock, and then stress would change in the surrounding bedrocks, which can be recorded on the ground plane near the bedrock or the deeper water level. An example was given by Clark (1982) who pointed out that the stress variation at the shallow depth agreed with the focal mechanism solution by analyzing the stress variation of a earthquake with M=2.1occurred in Lytle, Greek. Moreover, it clearly indicated that the deeper tectonic activity was transferred up to the depth of 20 m to the surface. Therefore, we suggest based on the above analyses that measuring the in-situ stress and monitoring continuously the stress changes in the seismic risk areas is possibly an effective method for seismologic surveillance and earthquake prediction.

References

Byerlee J D. 1978. Friction of rocks [J]. *Pure Appl Geophys*, **116**(4/5): 615~626.

CHEN Yu-ren, DING Xiang-huan, WANG Yao-dong. 1982. The recent activity of the NW-trending fault and seismicity in Fujian coastal area [A]. In: Commission for the Geology of Earthquakes, Seismological Society of China ed. The *Active Faults in China* [C]. Beijing: Seismological Press, 200~205 (in Chinese).

Clark B R. 1982. Stress changement monitoring of active fault in south California [J]. *J Geophys Res*, **87**: 4 645~4 656.

DING Xiang-huan, WANG Yao-dong, YE Sheng-ji. 1999. *The Active Fault and Seismicity in Fujian Southeast Coastal Area* [M]. Fuzhou: Science and Technology Press of Fujian Province, 197~210 (in Chinese).

HUANG Song-feng. 2003. The study on relation between Changzhao fault zone vertical movement and seismicity [J]. *Journal of Geodesy and Geodynamics*, **23**(4): 99~104 (in Chinese).

Hubbert M K and Willis D G. 1957. Mechanics of hydraulic fracturing [J]. *Trans AIME*, **210**: 153~166.

Jaeger J C and Cook N G. 1979. *Fundamentals of Rock Mechanics* [M]. London: Chapman and Hall Press, 97.

LI Fang-quan, ZHANG Bo-chong, SU Kai-zhi. 1993. *Reservoir Induced Earthquake Risk in Yangtze Gorges Dam Area* [M]. Beijing: Seismological Press, 191 (in Chinese).

LI Fang-quan, ZHANG Jun, LIU Peng *et al.* 1988. Hydraulic fracturing measurements in western part of Sichuan Province [A]. In: Institute of Crustal Dynamics, State Seismological Bureau ed. *Active Tectonics and Crustal Stress Field* [C]. Beijing: Seismological Press, 43~49 (in Chinese).

Rummel F. 1983. *Hydraulic Fracturing Stress Measurement Along the Eastern Boundary of the SW-German Block* [M]. Washington: National Academy Press, 3~17.

XIE Fu-ren, CUI Xiao-feng, ZHAO Jian-tao *et al.* 2004. Regional division of the recent tectonic stress field in China and adjacent areas [J]. *Chinese J Geophys*, **47**(4): 654~662 (in Chinese).

Zoback M D and Healy J H. 1984. Friction, faulting and in-situ stress [J]. *Annals Geophysicae*, **2**(6): 689~698.

Zoback M D and Hickman S. 1982. In site study of the physical mechanics controlling induced seismicity at Monticello reservoir south Carolina [J]. *J Geophys Res*, **87**: 6 959~6 974.