IOP Conf. Series: Materials Science and Engineering **392** (2018) 062077 doi:10.1088/1757-899X/392/6/062077

Research on In-situ Stress Testing of Deephole Cores from Earthquake Faults Using the Inelastic Strain Recovery Method1

Youzhong LU

Physical Science and Technology College Of YICHUN UNIVERSITY,

Xuefu Road, Yuanzhou District, Yichun, JiangXi 336000, China

E-mail:yz_lu@126.com

Abstract: The Wenchuan Earthquake Fault Scientific Drilling Project, a scientific drilling project that first responded to the Earthquake, performed deep 3D in-situ stress measurements using the inelastic strain recovery of core method for the first time under conditions whereby the borehole breakout method and hydraulic fracturing method could not be applied. The inelastic deformation of the deephole cores under the action of 3D stresses was simulated based on the inelastic strain recovery of viscoelastic body theory and core testing theory and the direction & magnitude of 3 major stresses were calculated under the precondition of homogeneous isotropy. In the field laboratory of the WFSD Project, the testing system developed was used to test the normal strain of inelastic recovery strain of deephole cores in 6 independent directions and determine the direction & magnitude of 3D in-situ stresses of the test points. In order to verify the effectiveness of the inelastic strain recovery method, an analysis was given into the testing result of #1 hole of the WFSD Project, which perfectly matches the result obtained by means of focal mechanism solution and other stress measurement methods, indicating that the inelastic strain recovery method is reasonable and reliable and is more applicable under complex geologic conditions whereby other in-situ stress testing methods cannot be applied. The method provides a new means for performing in-situ stress measurements using the core method under large-depth drilling conditions.

1. Introduction

In continental scientific drilling projects for scientific research purposes, the magnitude and direction [1-3,18] of 3D in-situ stresses are usually determined using the borehole method in combination with the core method. However, under large-depth drilling conditions, it is sometimes difficult to apply the drilling method. Hence, it is of great significance to explore new methods that are suitable for testing in-situ stresses of deep wells.

Wenchuan Earthquake Fault Scientific Drilling Project (WFSD for short), is the first scientific drilling project implemented by China on active faults following Wenchuan Earthquake, which requires rapid response and rapid drilling to obtain first-hand data[19] on the active faults. During the process of drilling of the deephole (3000m) of WFSD, the well reinforcing measure of applying bushing during the entire process was adopted to increase the drilling speed and make preparations for installing the long-term integrated monitoring system at the bottom of the well once the well was completed. The above objectives and measures of the Project require that the core method be adopted upon in-situ stress testing during the research process. For scientific deep drilling for which cores are taken during the entire process, 3D in-situ stress testing and research using cores is unprecedented in China. According to the general objective of the Project, the In-well Scientific Exploration research team of the WFSD Project developed the new testing methods and testing systems.

The research on in-situ stresses began in the 20th century when the domestic and overseas scholars carried out research on the formation and evolution of the geologic structure. In 1940s, the theory of geomechanics founded by Professor J.S.Lee (Li Siguang) included in-situ stresses. Since 1970s, with the adoption of many new technologies and methods, the measurement of in-situ stresses entered the quantitative research stage [4-7,20]. Reference literature [21] provides a summary of the measurement methods of in-situ stresses, holding that the research methods of in-situ stress measurement can generally be categorized as follows:

(1) Method of inference from the rock mechanics testing data;

(2) Estimation of the magnitude of the shearing stress based on the magnitude of the conjugate angles upon conjugate shearing and the shear heat dynamometamorphic rock in the faults;

(3) Microstructure and ultra-microstructure estimation method;

(4) Drilling method;

(5) Hydraulic fracturing;

(6) Measurement and estimation of the in-situ stress using the acoustic emission method or measurement of horizontal in-situ stresses in the main direction using the dipmeter or underground TV.

However, as the above methods have their limitations, the scientists then focused their research on the method of performing in-situ stress measurements using borehole cores, namely the core method, which includes the differential strain curve analysis (DSCA) method, inelastic strain recovery method (ASR), deformation rate method (DRM), etc[8-17]. In the past, the ASR method could be used to carry out 2D in-situ stress measurement only in the past research work, that is, assuming the rock is linearly viscoelastic and the stress in the vertical direction is one main stress and equal to the pressure of the covering layer, which means that the inelastic strain recovery (inelastic strain change resulting from graded unloading of unit stress) is independent of the acting stress and the error of the magnitude of the in-situ stress measured at this time is large[22]. Koji Matsuki carried out in-depth research on the ASR method, thinking that 3D measurement [23,24] may be performed in theory, and Lin W et al, have kept research on this topic in the recent years[25].

According to the In-well Scientific Exploration research team, under conditions of normal stresses, considering the inelastic normal strain recovery of the deephole cores as the isotropic, viscoelastic material in any direction, the new method of in-situ stresses determined by measuring 6 independent inelastic normal strains, together with the test system for inelastic recovery test of cores, provides a new means for research on in-situ stresses of deepholes.

2. Inelastic Strain Recovery Method and Test Technology

2.1 Theoretical basis of the inelastic strain recovery method

In the ASR method, simulation of deformation of the cores over time after the stress is released is the pre-condition. The core deforms under the action of the 3D in-situ stresses under the initial conditions; once the stress is released, part of deformation of the core is recovered instantly, which is elastic deformation. Another part of deformation does not reach the elastic deformation value immediately and there is a relative delay, which is called inelastic recovery deformation.[26-27]. As elastic deformation that is recovered instantly is difficult to capture in in-situ stress measurements, people use inelastic recovery deformation for stress measurements. In the research on the rheological property of rock, the 2-element rheological model of the viscoelastic body is generally adopted (as shown in Figure 1)[24-26,28].

However, as the model can not reflect the rapid change in initial inelastic strain recovery observed in the laboratory, the 4-element rheological model of two delays are introduced to reflect the entire property of inelastic strain recovery (Figure 1). For simplicity purpose, the rock is assumed to be isotropic, viscoelastic material that has two different deformation methods: shearing deformation and volume deformation.

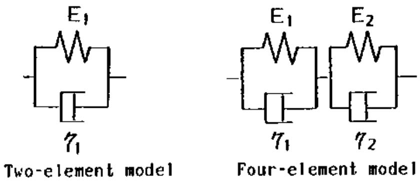

Figure 1 Linear viscoelastic models for inelastic strain recovery of rocks

Assuming the rock under general 3D stress and pore pressure P0 is flexible, the cosine (l, m, n) normal strain (corresponding to axis X,Y ,Z) in any direction may be written as (Figure 2):

$$\varepsilon = (1/E)(l^2\sigma_x + m^2\sigma_y + n^2\sigma_z + 2lm\tau_{xy} + 2mn\tau_{yz} + 2nl\tau_{zx})$$
$$+(\nu/E)\begin{bmatrix}(m^2+n^2)\sigma_x + (n^2+l^2)\sigma_y + (l^2+m^2)\sigma_z \\ -2lm\tau_{xy} - 2mn\tau_{yz} - 2nl\tau_{zx}\end{bmatrix}$$
$$-(1/3)(1/K - 1/K_S)P_0 + \alpha_T \Delta T$$

(1)

Where, E-Young's modulus; ν -Poisson's ratio, K-apparent bulk modulus, KS- mother rock apparent bulk modulus, α_T - linear thermal expansion coefficient, ΔT -temperature increment.

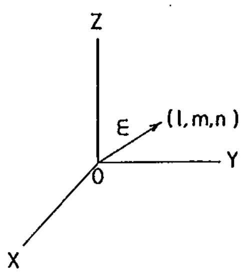

Figure 2 Normal strain in an arbitrary direction in a viscoelastic body subjected to general stress

For the isotropic viscoelastic materials, using the similar theory in the LapLace transform solution and the inelastic strain recovery flexibility, at t=0, the in-situ stress and the pore hydraulic pressure began to be relieved gradually, and the inelastic strain recovery $\varepsilon_a(t)$ in any direction may be obtained through the formula below:

$$\varepsilon_a(t) = (1/3)[(3l^2-1)\sigma_x + (3m^2-1)\sigma_y + (3n^2-1)\sigma_z +$$
$$6lm\tau_{xy} + 6mn\tau_{yz} + 6nl\tau_{zx}]Jas(t) + (\sigma_m - P_0)Jav(t) + \alpha_T \Delta T(t) \quad (2)$$

Where, σ_x , σ_y , σ_Z , τ_{xy} , τ_{yz} , τ_{zy} - components of in-situ stress tensor of the drill; σ_m - average normal stress; $Jas(t)$, $Jav(t)$ - shearing strain recovery flexibility, bulk strain recovery flexibility.

In ASR measurements, due to sufficiently high accuracy of the test system developed and tiny impact of the temperature, thermal expansion strain resulting from temperature changes in formula (2) may be ignored. Formula (2) provides the basis of the ASR method, indicating that inelastic strain recovery is dependent on 6 independent normal components in in-situ stress tensor, pore hydraulic pressure and inelastic strain recovery flexibility of two deformation methods. Hence, if the inelastic strain recovery flexibility ($Jas(t)$, $Jav(t)$) and pore hydraulic pressure P0 (may be obtained upon well logging) are known, the 6 normal stress tensors (namely 3D in-situ stress tensor) may be obtained by measuring at least 6 independent directions of the inelastic strain.

For the isotropy viscoelastic materials, the direction of the 3 principal stresses is identical with the main axis of the 3 inelastic strain tensors. Hence, the direction of the 3D principal stress may be determined by measuring the inelastic strain tensors, that is, determined by measuring the normal strain of at least 6 independent directions.

Principal stress deviator:

$$s_i = \sigma_i - \sigma_m (i = 1,2,3) \qquad (3)$$

Where, s_i - principal stress deviator s_1, s_2, s_3; σ_i -3 principal stresses σ_1, σ_2, σ_3; σ_m - average principal stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$ 。

Principal stress deviator:

$$e_i = \varepsilon_i - e_m (i = 1,2,3) \qquad (4)$$

Where, e_i -principal stress deviator e_1, e_2, e_3; ε_i -3 principal stress ε_1, ε_2, ε_3; e_m -average principal strain $e_m = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3$.

The theory can prove that the ratio of the principal stress deviator may be determined by the principal strain deviator. If the rock is isotropy in mechanics and thermics, when the inelastic normal strain in 6 independent directions is replaced by inelastic strain deviator e_{ija} ,

$$e_{ija}(t) = (1/3)[(3l^2-1)\sigma_x + (3m^2-1)\sigma_y + (3n^2-1)\sigma_z + 6lm\,\tau_{xy} + 6mn\,\tau_{yz} + 6nl\,\tau_{zx}]Jas(t) \qquad (5)$$

Under conditions of unknown pore pressure and temperature changes, the ratio of the 3 principal stress deviators and the azimuth angle of the principal stress are determined by the 6 inelastic strain deviators.

The inelastic strain recovery flexibility varies with the average stress, and its dependence on the average stress is mainly affected by short-term deformation. However, since it generally takes some time to bring the cores from deep holes to the ground, the long-term strain recovery is more important for in-situ stress measurement. In long-term deformation, the average stress does not affect the inelastic strain recovery flexibility in the shearing mode. However, for the volume mode, its impact may not be ignored[22-23]. Hence, in (5), if the dependence of the inelastic strain recovery flexibility in the shearing mode on the average stress can be ignored, the information about it may be unnecessary,

Moreover, the inelastic average normal strain e_a may be expressed as:

$$e_a(t) = (\sigma_m - P_0)J_{ar}(t) + \alpha_T \Delta T \qquad (6)$$

Due to the high accuracy of the ASR test system and tiny effects of the temperature, thermal expansion stress resulting from temperature changes in the above formula is ignored; the pore pressure P0 may be measured upon well logging. Hence, when determining the magnitude of the absolute value of the in-situ stress, the same core specimen may be used in the laboratory to test the change of the inelastic strain recovery flexibility and its change with the average stress in the volume mode and then the iteration method may be used in combination with the ratio of the 3 principal stress deviators determined in formula (5) to determine the magnitude of the absolute value of the 3D in-situ stress.

During the drilling process, inelastic strain recovery of the cores generally lasts several days and even weeks. The duration of the ASR depends on rock type and the size of the average normal stress. Once the core is obtained from the deep holes, the ASR measurement shall be performed as soon as possible. The reason is that once the stress is released, the value of inelastic strain may decrease over time and the recovery rate becomes smaller. As a result, an on-site laboratory is generally launched for measurement using the ASR method to avoid delay during the transport of the core. In normal cases, the ASR measurement may not be performed immediately after the stress is released and the inevitable delay (namely the interval between the time that the stress is released and the time that the measurement begins) depends on the depth from the core to the ground surface and the time taken to prepare the ASR specimen. In the opinion of K.Matsuki, if the flexibility used is the same interval of measurement time (t_0 to t), the above method can be applied [29].

2.2 Preparation of the specimen for the inelastic strain recovery method

The WFSD Project has set up a special laboratory on the scientific drilling site to carry out the ASR test, the cores of which are all taken from the WFSD-1, WFSD-2 and WFSD-3 deep holes from the faults of Wenchuan Earthquake. The cores from the boreholes are scanned after being taken out and compared with the well logging data for locating.

In order to shorten the time interval between the release of the stress and the commencement of the ASR test, it is required that the test section be lifted once for every 2 ~ 3m long core drilled (Figure 3) during the drilling process. Once the core is lifted onto the ground, a no less than 20cm long homogeneous crack-free core section shall be selected immediately from the deep end of the core as the specimen for cleaning, orientation and locating and be photographed in all directions (for comparison and locating).

Figure 3 Core from the deep hole of WFSD

To measure 3D in-situ stresses using cores, the normal strain of the inelastic strain in all of the 6 independent directions must be determined as the normal stress status contains 6 components. This study adopts 6 specially devised strain schemes to measure normal strains in the 6 independent directions. When these 6 components are obtained, the entire inelastic strain can be determined (Figure 4).

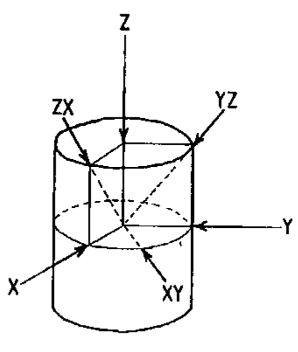

Figure 4 Normal strains to be measured for determining three-dimensional in-situ stresses with ASR method

In the low-temperature field laboratory, the surface of the specimen is dried rapidly, the part of the specimen where the strainometers will not be pasted is polished with abrasive paper, and the strainometers are pasted in the manner shown in Figure 5. 3 groups of strainometers are pasted and each group consists of 4 single linear strainometers, which test the inelastic strain recovery along the axial direction (or X axis), horizontal direction (or Y axis) of the cores, +45° and -45° directions (12 directions in total) (Figure 6). To avoid the effects of temperature changes on conductor resistance, the same connection method and bridge circuit are used.

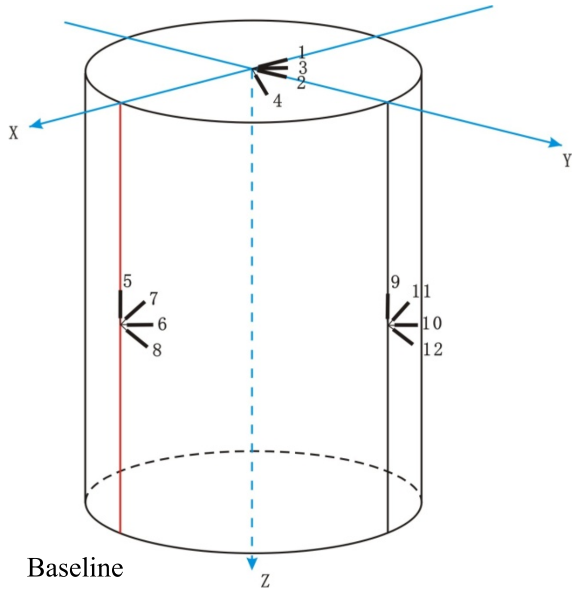

Figure 5 Schematic layout of specimen surface strain gauge with ASR method

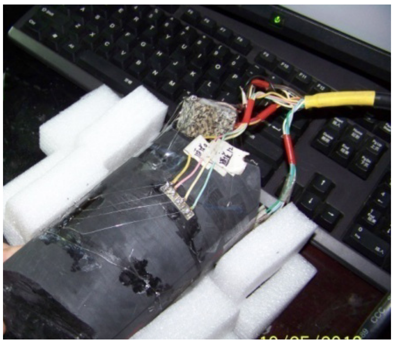

Figure 6 Paste method of strain gauge with ASR test methods

2.3 AST Measurement System

In the WFSD Project, the "In-Well Scientific Exploration" research team developed the ASR test system independently and developed the tester as shown in Figure 9. The system mainly consists of the tester (constant temperature, low humidity), data collector and recorder (including the main unit) and the uninterruptable power supply (UPS), etc.

Among them, the tester is used for continuous testing of the specimen that is put into it under conditions of constant temperature and low humidity, the collector and recorder is used to collect and record the strain data, and the UPS is used to prevent measurement problems resulting from power failure. The system adopts the scheme of simultaneous measurement of the specimen and the compensation specimen, which is subject to no other deformation except the deformation as a result of thermal expansion. The purpose of compensation specimen measurement is to monitor system drift. The rock used for preparing the compensation specimen is extracted from the ground surface and shall have the same or similar properties as the test specimen. The two specimen are put into the tester under conditions of constant temperatures and low humidity for testing. To avoid temperature-induced deformation of the specimen as a result of significant temperature differences, the internal temperature of the tester was set up so that it is close to room temperature. The strain sensor is connected to the data collector and the data collected are uploaded to the operating computer for recording.

Research on the ASR test is carried out in the field laboratory of the WFSD project, the cores used are lifted from the bottom of the well to the ground surface and then processed on the site, including cleaning, determination of direction, locating, photographic recording and preliminary rock property description, the preparation of the ASR specimen is completed and the strain measurement test is commenced officially within 5h after the stress is released. As described above, under normal conditions, inelastic strain recovery after the core stress is released will last several days or weeks and the test does not require a complete ASR curve (from the release of stress to strain convergence). That is to say, if the strain recovery curve is stable and the strain value is large in relative to the accuracy of the test system, part of the strain recovery curve is sufficient for the research [25]. Hence, the time of the ASR measurement is generally 1 week or so.

3. Test results and analysis

The measurement time of all inelastic train recovery tests conducted on the site is about 1 week. The geologic background of the faults of Wenchuan Earthquake is given in the reference literature[30]. The tester developed operated normally during the test process and the temperature change was less than ±0.1℃. The strain data of the compensation specimen indicate that the drift of the measurement system and thermal expansion is tiny and negligible and the ASR test produced satisfactory results. Below is the typical test result of #1 hole of scientific exploration of the faults of Wenchuan Earthquake[28].

The cores were obtained from a depth of 746m, the strain recovery curve was stable and increased with time, the inelastic strain recovery value increased rapidly initially and slowly later, meeting the law of change of inelastic strain and the number of strains reached more than 100 microstrains and the accuracy fully met the measurement requirements.

The 3 principal strains and average strains are calculated based on the strain recovery curves in 6 directions using the least square method and through correction of the direction of the core coordinate axis and well inclination. Among the isotropic materials, the direction of the principal strain is identical with that of the principal stress, as a result of which the direction of the principal strain is the direction of the principal stress. The maximum principal stress σ_1 and the medium principal stress σ_2 are close to horizontal, the minimum principal stress σ_3 is close to vertical, the direction of the maximum principal stress σ_1 is north west 49°, close to orthogonal to the direction of the faults of Wenchuan Earthquake; the magnitude of the 3 principal stresses are calculated using the iteration method in combination with Formula (5) to be:25.2MPa, 21.5 MPa and 18.5 MPa. This stress status results in thrust and dextral strike-slip of the faults of the Wenchuan Earthquake, which is consistent with the type of movement of faults of Wenchuan 5·12 Earthquake.

By comparing the test result of the ASR method and the focal mechanism solution of the Wenchuan “5·12” MS8.0 earthquake, it can be learned that their direction and dip angle are very close.

By comparing the test result of the ASR method and the in-situ stress measurement result of the area shit by Wenchuan Earthquake, it can be learned that the direction of the maximum horizontal principal stress obtained using the ASR method is identical with the result obtained using other in-situ stress measurement methods in the adjacent areas, both being in the north-west and north-west-west directions.

An analysis of the plenty of inelastic strain recovery tests of the WFSD-1, WFSD-2 and WFSD-3 deep holes indicates that the test results have the following characteristics:

(1) The test specimen experiences extensible inelastic recovery strain in all directions with smooth strain curve and similar trend of change with time. Obviously, the inelastic strain in all directions last longer than one week, but the strain recovery rate decreased over time.

(2) After measurement of nearly 1 week, the magnitude of strains in all directions reached 100 microstrains. Since large microstrain can ensure the measurement accuracy, the data can be used for 3D in-situ stress analysis. In comparison with the conventional rock mechanics test (for instance, single axis or 3-axis compression test), the inelastic strain value is about 1% of the axial strain value of the rock in the extreme collapse state.

(3) According to the measured inelastic strain value in 12 directions, the least square method was used to calculate the inelastic normal strain values in 6 independent directions and determine the inelastic strain tensors. The ratio of the 3 principal strain deviators and their azimuth angles may be obtained according to formula (5). Due to the tiny effects of temperature in measurement using the ASR method, thermal expansion strain resulting from temperature changes may be ignored, and the underground rock pore pressure P0 can be obtained upon well logging. Then, using formula (6), the same core specimen is used in the laboratory to test the relationship of the inelastic strain recovery flexibility in the volume mode changing with the average stress and the iteration method is used in combination with Formula (5) to determine the magnitude of the absolute value of the 3D in-situ stress. The in-situ stress test result obtained through the research is close to the result obtained using other methods such as focal mechanism solution and hydraulic fracturing in-situ stress measurement, indicating that the test result obtained through this study is reasonable and effective.

4. Conclusions

(1) The Wenchuan Earthquake Fault Scientific Drilling Project, a scientific drilling project of the humans that first responded to the Earthquake, examined the ASR method for cores of deephole (3km) in-situ stress test , developed the new test system and devised the test scheme under conditions whereby the borehole method can not be applied and based on the rock viscoelasticity theory, providing a means for carrying out in-situ stress measurements using the core method under conditions of large-depth drilling.

(2) After the laboratory is established on the site and the cores are lifted from the deed holes to the ground surface, a no less than 20cm long homogeneous, crack-free core section is selected from the deep end of the core as the specimen, which is then processed on the site, including cleaning, determination of direction, locating and photographic recording. Under conditions of low humidity, the surface of the specimen is dried rapidly, the strainometers are pasted in 12 directions, the specimen is then put into the constant temperature, low humidity test box, the data collection and recording device of the test system operates continuously for one week and the normal strain of inelastic recovery strain of cores in 6 independent directions is obtained.

(3) The direction and magnitude of the 3 principal stresses of the hole depth corresponding to the test core section are calculated using the test curve and the theory calculation method. Take #1 hole of the WFSD Project, at the 746m vertical depth of the hole, the maximum principal stress σ_1 and the medium principal stress σ_2 are close to horizontal, the minimum principal stress σ_3 is close to vertical, the direction of the maximum principal stress σ_1 is north-west 49° and its magnitude is 25.2MPa, 21.5 MPa and 18.5 MPa respectively. The test result perfectly matches the result obtained by means of other stress measurement methods such as focal mechanism solution and hydraulic fracturing, indicating that the inelastic strain recovery method is reasonable and reliable for 3D in-situ stress measurement of deep holes.

(4) To ensure the accuracy of the test, when testing the strain, it is essential to test a non-deforming rock specimen that is taken from the ground surface and has the same or similar properties

simultaneously to monitor the operating status of the test system. The measurement accuracy of the ASR method is determined by the conditions of the core itself and the orientation accuracy. Generally speaking, the error of the direction angle is less than ±10° and the error of the stress value is less than ±10%.

(5) For the laboratory established on the site of the Earthquake, there are many limitations and the power supply is usually not stable. To prevent loss of the test data as a result of faults in power supply, the test system is provided with the manual saving function. To ensure 100% data security, the auto-saving function of the system shall be developed on the basis of the manual saving function.

Acknowledgments
Science and technology research project of Jiangxi Provincial Education Department （No.GJJ170913）

References

[1] John Langbein.Computer algorithm for analyzing and processing borehole strainmeter data [J].Computers & Geosciences, 2010, 36(5):611-619.
[2] Brodsky E E, MA Kuo-Fong, Saffer J MM . Rapid response fault drilling: Past, present and future ［J］ . Scientific Drilling, 2009, 8: 66-74.
[3] Zhang P Z, Shen Z, Wang M, et al.Continuous deformation of the Tibetan Plateau from Global Positioning System data[J].Geology, 2004, 32: 809-812.
[4] Tanaka H, Chen W M, Wang C Y, et al . Frictional heat from faulting of the 1999 Chi-Chi, Taiwan earthquake ［J］ . Geophysical Research Letters, 2006, 33 (L16316): 1-5.
[5] LIN Weiren.A core-based method to determine three-dimensional in-situ stress in deep drilling wells:anelastic strain recovery technique[J] .Chinese Journal of Mechanics and Engineerring, 2008, 27 (12) : 2 387-2 394.
[6] Wong Teng-fong.Weakening msechanisms for faulting associated with large slip: hydromechanical constraints from laboratory measurement ［EB / OL］ . (2004-01-20) ［2010-11-26］ . http: / / eqkc . earth . ncu . edu . tw / TCDP /03TFWong . pdf
[7] Yasuyuki Kano, Jim Mori, Ryo Fujio, et al. Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake[J]. Geophysical Research Letters, 2006, 33(L14306): 1-4.
[8] Wallace R E . The San Andreas Fault System, California: U S Geological Survey Professional Papers ［M］ . Washington:United States Government Printing Office, 1990 .
[9] d'Alessio M A, Bürgmann R . Constraints on frictional heating of faults from fission track thermochronology ［EB /OL］ . ［2010-11-26］ .http:/ /seismo .berkeley .edu/annual_ report/ar00_ 01 /node20 . html
[10] Yamada Ryuji, Matsuda Tatsuo, Omura Kentaro . Zircon fission-track dating of NIED Nojima fault drilling cores at irabayashi borehole［J］.The Earthquake Engineering Online Archive, 2005, (755 R46): 272-273 .
[11] Fukuchi T, Mizoguchi K, Shimamoto T . ESR detection of frictional heat in seismic fault slip ［C］ / /American Geophysical Union.Abstracts of American Geophysical Union Fall Meeting . Washington : American Geophysical Union, 2001: #T22A-0897
[12] Tani Atsushi, Omura Kentaro, Ikeda Ryuji . ESR investigation of a thermal history on Hirabayashi NIED drilling core penetrating the Nojima Fault［J］.Report of the National Research Institute for Earth Science and Disaster Prevention, 2001, 231-236.
[13] MATSUKI K.Three-dimensional in-situ stress measurement with anelastic strain recovery of a rock core[C]// WITTKE W ed.Proceedings of the 7th International Congress on Rock Mechanics.

IOP Conf. Series: Materials Science and Engineering **392** (2018) 062077 doi:10.1088/1757-899X/392/6/062077

Aachem：[s.n.],1991：557 – 560.
[14] MATSUKI K，TAKEUCHI K.Three-dimensional in-situ stress determination by anelastic strain recovery of a rock core[J] .International Journal of Rock Mechanics and Mining Sciences and GeomechanicsAbstracts,1993,30(7)：1 019 – 1 022.
[15] Koji Matsuki. Anelastic strain recovery compliance of rocks and its application to in situ stress measurement [J] .International Journal of Rock Mechanics & Mining Sciences， 2008，45：952–965.
[16] MATSUKI K. Theoretical examination of the method for measuring three-dimensional in-situ stresses with anelastic strain recovery of rock core[J] .Journal of Mining and Materials Processing Institute of Japan,，1992，108(1)：41-45.
[17] Benioff H,，Press F and Smith S．Excitation of the free oscillations of the earth by earthquakes [J] ．Journal of Geophysical Research，1961，66(2): 605-619.
[18] XU Jiren, ZHAO Zhixin, XU Zhiqin, et al. New progress in continental scientific drilling and long-term geophysical observations in deep boreholes[J]. Geological Bulletin of China, 2004,23(8):721-727.
[19] XU Zhiqin，LI Haibing，WU Zhongliang. Wenchuan Earthquake and Scientific Drilling[J]，Acta Geologica Sinica，2008，82（12）：1613-1622. (in Chinese)
[20] Cai Meifeng. The principle and technology of in-situ stress measurement [M]. Beijing: Science Press, 2000.3-6.(in Chinese))
[21] Zhou Zuhui. In-situ stress of nonlinear rheological formation by ASR method of a rock core [J].Oil Drilling and Production Technology，1990，（1）：1-6.(in Chinese)
[22] MATSUKI K. Three-dimensional in-situ stress measurement with anelastic strain recovery of a rock core[C]// WITTKE W ed. Proceedings of the 7th International Congress on Rock Mechanics. Aachem：[s.n.],1991：557 – 560.
[23] MATSUKI K, TAKEUCHI K. Three-dimensional in-situ stress determination by anelastic strain recovery of a rock core[J] .International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts,1993,30(7)：1 019 – 1 022.
[24] Koji Matsuki. Anelastic strain recovery compliance of rocks and its application to in situ stress measurement [J]. International Journal of Rock Mechanics & Mining Sciences， 2008，45：952–965.
[25] Lin Weiren. A core-based method to determine three-dimensional in-situ stress in deep drilling wells: anelastic strain recovery technique [J]. Chinese Journal of Rock Mechanics and Engineering，2008，27(12)：2 387–2 394.(in Chinese)
[26] Yin Xiangchu. Solid mechanics [M] .Beijing: Seismological Press, 1985.1-512. (in Chinese)
[27] Jaeger JC, Cook NGW. Fundamentals of rock mechanics [M]. Translated by Institute of Engineering mechanics, Chinese Academy of Sciences Translated. Beijing: Seismological Press,1981.(in Chinese)
[28] Wang Lianjie, Sun Dongsheng, Lin Weiren, et al. Anelastic strain recovery method to determine in-situ stress and application example[J] . Chinese Journal of Geophysics, 2012，55（5）：1 674-1 681. (in Chinese)
[29] MATSUKI K. Theoretical examination of the method for measuring three-dimensional in-situ stresses with anelastic strain recovery of rock core[J] .Journal of Mining and Materials Processing Institute of Japan，1992，108(1)：41-45.
[30] Wang Lianjie，Cui Junwen，Zhou Chunjing，et al. Numerical modeling for Wenchuan earthquake mechanism [J]. Journal of Geomechanics，2009，15(2)：105-113. (in Chinese).