Present-day Geostress Characteristics of the Central Region of the 1605 Qiongshan M 7.5 Earthquake and their Implications for Regional Fault Activity

X Ma[1,2,3], H Ji[1], J Bai[4], L Jia[2,3]*, Y Sun[2,3], J Jiang[2,3], X Du[2,3]

1. Beijing Key Laboratory of Urban Underground Space Engineering, University of Science and Technology Beijing, Beijing 100083, China
2. Field Sciences Observation and Research Station of Crustal Stress and Strain in Beijing, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China
3. Institutes of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China
4. China Power Construction group Beijing Survey Design & Research Institute Co., Ltd., Beijing, 100024, China

ABSTRACT

Continuous subsidence, which has occurred over more than 100 km^2 of the Dongzhai Harbor area, northeast Hainan Island, is likely to be associated with tectonic movement arising from the 1605 Qiongshan M 7.5 earthquake. It is the only earthquake in the history of China to have caused large-scale land subsidence into the sea, and the disaster led to the sinking of 72 villages. To understand the dynamic environment of this subsidence, a 300-meter-deep borehole was established on the eastern side of the Puqian town on the east coast of Dongzhai Harbor. A series of 10 in-situ stress measurements and 4 impression orientation measurements were carried out by the hydraulic fracturing method in the borehole. The results show that the maximum horizontal principal stress, S_H, is between 5.70 to 12.07 MPa, and the minimum horizontal principal stress, S_h, is between 4.13 to 8.16 MPa. Compared with the magnitude of in-situ stress in the South China coastal area, the magnitude of the in-situ stress for Dongzhai Harbor is considered to be of a medium to upper level. The maximum horizontal principal stress direction is in the northwest direction (33.96 NW). The maximum and minimum horizontal lateral pressure coefficient values are both greater than 1, which indicates that the stress field at the measured point is mainly horizontal, with the principal stress increasing with the depth. The NW-trending principal compressive stress is likely to be one of the dynamic sources of the activity of the Puqian - Qinglan fault and the subsidence of the Dongzhai Harbor graben.

1. INTRODUCTION

Since the Qiongshan 7.5 magnitude earthquake of 1605, there has been continuous subsidence in the Dongzhai Harbor area, northeast Hainan, with a subsidence range of up to 10 meters [1, 2],

*Corresponding Author: jialiyun@mail.cgs.gov.cn

which has a significant impact on the crustal stability of the region of Northeast Hainan Island. As natural stress exists within the Earth's crust, geostress provides the most direct measure of the driving forces behind deformation in the crust, tectonic movement, and even the triggering of earthquakes. Research on the regional stress field has been conducted around the southeast coast and the northern areas of the South China Sea, in the vicinity of the epicenter of the 1605 Qiongshan Earthquake [3-5] by means of techniques such as focal mechanism solution analysis and the numerical simulation of the expected stress field. This raises several questions, namely what is the current state of the local geostress field in the region of Dongzhai Harbor, and does it play a role in controlling or influencing the sedimentation conditions in Dongzhai Harbor?

Until now, the relationship between geostress and tectonic subsidence has never been reported. Measurements of in-site stress through the hydraulic fracturing method have been regarded as one means of measuring a rock mass's stress as recommended by the Test Methods Committee of the International Society of Rock Mechanics and is considered to be one of the most direct and effective methods in determining the crustal stress state. Numerous domestic researchers have undertaken a large number of studies on in-situ stress using this method [6-15], while conducting further studies from the perspective of the associated stress field and crustal structure [16-22]. Therefore, through all these efforts, this technique has achieved considerable acceptance for other applications, being widely used in several national key constructions project with regards to assessing earthquake [23-25] , mine engineering, and tunnel engineering, water conservancy and hydropower engineering [26-30], nuclear waste disposal engineering [31-33], resolving the location of oil reserve [34], fault stability analysis [35], as well as theoretical studies into earth dynamics [36-44]. To investigate the current geostress state of Dongzhai Harbor, the hydraulic fracturing in-situ stress measurement method was used to obtain the relevant data, so as to provide geodynamic evidence for structural stability, earthquake risk, and graben subsidence in this area.

2. THE GEOTECTONIC ENVIRONMENT

Dongzhai Harbor is located at the southeastern Leiqiong sag (Fig. 1), Hainan province, south to the Qiongzhou Strait, with two groups of faults, namely the Mainiao-Puqian fault (MPF) and the Puqian-Qinglan fault (PQF), located here, both of which are hidden active faults [45]. The eastern segment of the MPF is located in the Dongzhai Harbor area, extending toward the NEE, with an inclination in general towards the NNW, and some sections inclining to the SSE, cut by other faults striking towards the NW into discontinuous distributions with numerous sections, resembling a ladder. The MPF is a Holocene active fault and was the source of the M7.5 1605 Qiongshan earthquake. It is located in an area that experiences both the maximum shearing stress and the principle compressive stress for this region [46]. The Dongzhai Harbor section of the PQF is separated into two branches striking along the eastern and western sides of the harbor, extending toward Puqian Port and Yan Feng County, respectively, extended into the Qingzhou Strait. The strike of the eastern branch is NNW, and for the western branch it is NW, with the whole length of the fault being nearly 60 kilometers, with the branches separated by 11 km at their widest part. The distribution of the faults and earthquakes in the study area is shown in Fig. 1.

According to historical records [1, 2] and our fieldwork, the interactions between the PQF and the MPF are believed to have led to the section from Yan Feng to Tashi to be regarded as the epicenter of the 1605 Qiongshan M7.5 earthquake, whose isolines reveal that the seismic intensity was extended and distributed along the two groups of faults. In addition, within the environment of the tectonic stress field, the subsidence trend of the Dongzhai Harbor area has continued until now.

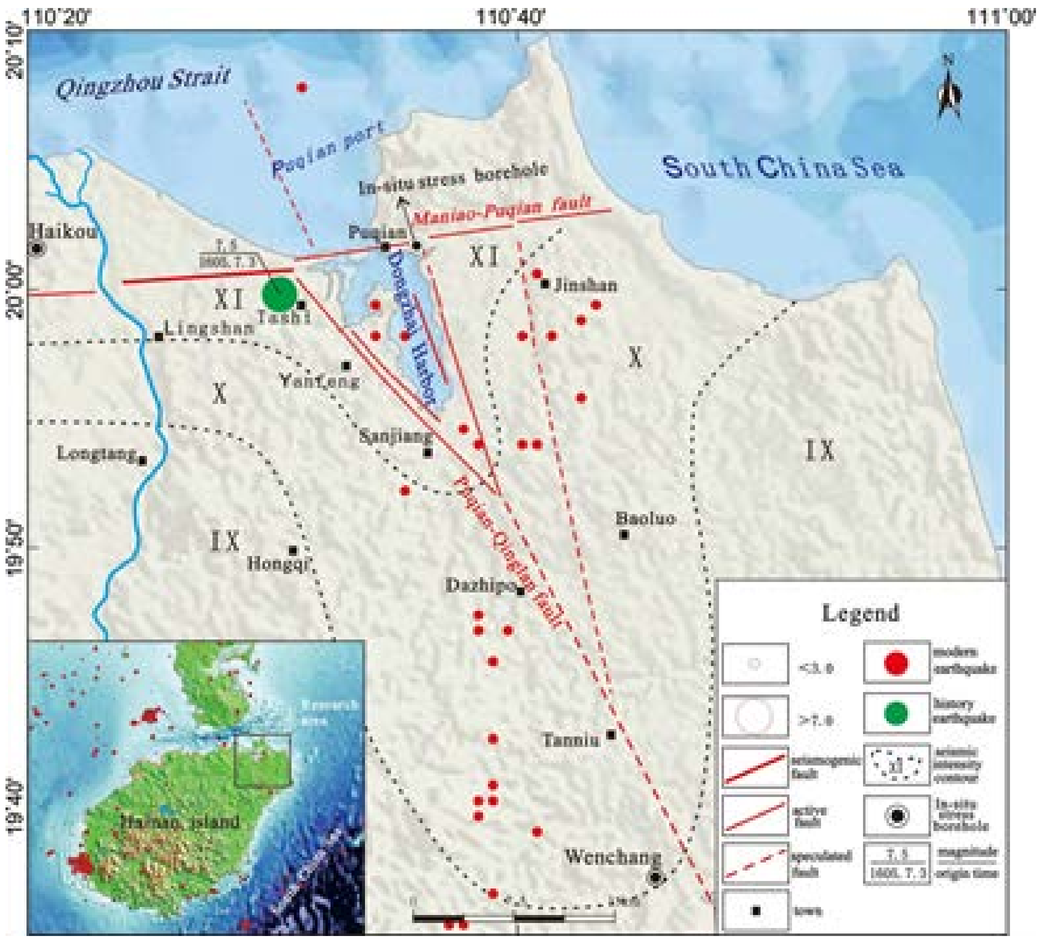

Fig.1 Distribution of faults and earthquakes in northeast Hainan (modified after Chen and Huang, 1979; Ding et al., 2018)

Based on the borehole data [47] since the Neogene, the sedimentary center in the region of Dongzhai Harbor has been enduring a mitigation process from west to east, with a sharply increasing deposition rate after the Neogene, which is regarded as the highest observed rate in the world. Therefore, under the influence of the current in-situ stress field in the Dongzhai Harbor region, the Holocene MPF and PQF have jointly controlled the subsidence of the fault depression in this region.

3. METHODS AND MATERIALS

3.1 The in-situ stress hole construction

The borehole used for the in-situ stress measurements is located on the eastern side of Dongzhai Harbor, Puqian Town, at the intersection between the eastern branch of the PQF and the MPF, with moderate topographic features (Fig. 1). The depth of the borehole is 301.95 meters, with water at a depth of 0.5 meters, revealing silty clay from the Quaternary period (0 ~ 7.93 m), as well as relevant lithologic categories such as the Yanshanian granites under ~7.93 depth (Fig. 2). The integrity of the drilled core was high, with more than 90% of the columnar cores, being retrieved a number of times in the form of 3m long columnar cores and only one developed fissure about 130 ~ 140 m in the whole borehole being encountered (Fig. 2), The borehole was cased from 0 ~ 12 m, with a drilling diameter of Φ146 mm. The uncased borehole section was from 12 m to the borehole bottom, with a drilling diameter of Φ130 mm and the borehole having a relatively smooth wall. All of those factors have provided qualified borehole and formation conditions for the measurement of in-site stress. To obtain the current state of the in-situ stress of this borehole, 10 in-situ stress measurement sections and 4 impression orientation segments were selected from between 30 ~ 300 m at depth (Fig. 2).

3.2 In-situ stress measurement by hydraulic fracturing

The in-situ stress measurement by hydraulic fracturing system was developed by Institute of Geomechanics, Chinese Academy of Geological Sciences (CAGS). As shown in Fig. 3a, a pair of rubber packers is used to seal a selected testing section, known as the fracturing section. Next, fluid materials are pumped into the fracturing section, until vertical cracks form in the wall of the borehole under fracturing pressure. After releasing the pressure, the fracturing fluids are injected into the sealed section again to make the previously formed vertical cracks open again and extend to 2 to 3 m, and then the pressure is again released. This procedure needs to be repeated three to four times to finish the experiment while recording the pressure-time curve (Fig. 3b). The direction of the vertical fracture during the fracturing stage is then obtained by the impression and orientator (Fig. 3c).

Fracturing process: 1. Pack the borehole section. 2. Pressurize the fracturing section. 3. The walls of the borehole fracture and led to cracks. 4. The cracks close. 5. The pressure is released. Reopening process: 6. Pressurize the fracturing section again. 7. The original fractured cracks reopen. 8. The fractures close. 9. Releasing the pressure.

According to the tested curve (Fig. 3b), the blasting pressure of the borehole's wall, P_b, the instantaneous closing pressure, P_s, and the re-opening pressure, P_r, can be retrieved. From these values, the following can be calculated [48-50]:

$$T = P_b - P_r \tag{1}$$

$$S_H = 3P_s - P_r - P_0 \tag{2}$$

$$S_h = P_s \tag{3}$$

$$Sv = \rho g H \tag{4}$$

where T is the rock's tensile strength, S_H is the largest horizontal principal stress, S_h is the minimum horizontal principal stress, and S_v is the lead-straight principal stress, with P_0 the

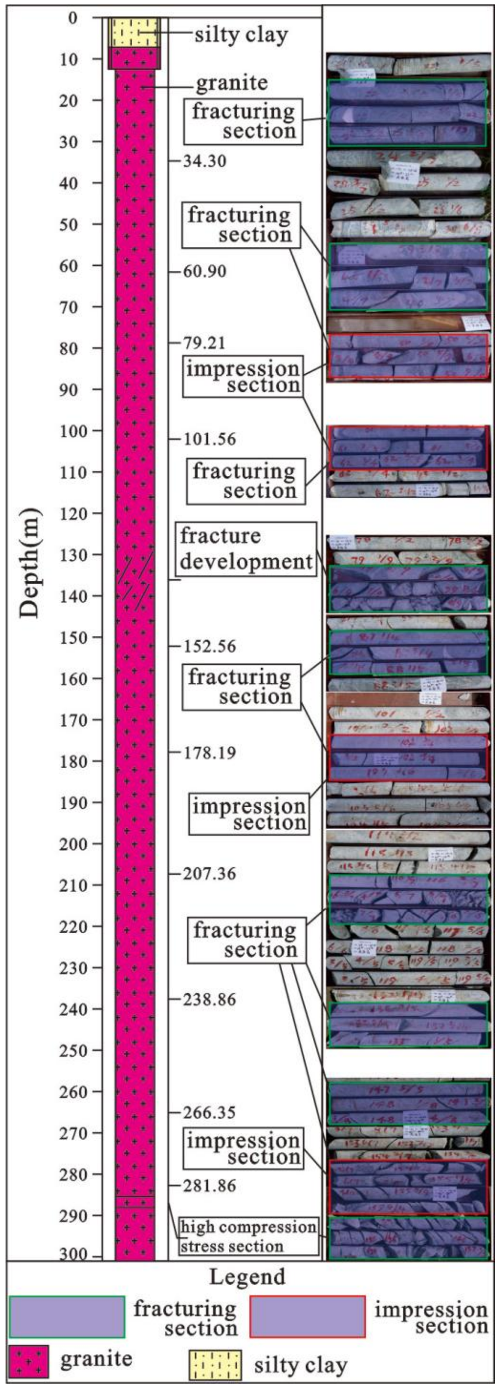

Fig. 2 In-situ stress and impression orientation measuring sections of the borehole. Fracturing and impression sections refer to the length over which the measurements were made.

pore pressure, ρ the average density of overlying strata, g the gravitational acceleration, and H the thickness of the rock overlying the fracturing section.

In equation (1), the pore pressure is one of the parameters used to determine the maximum horizontal principal stress. Among those rocks with low permeability in the shallow part of the crust, the pore pressure is approximately equivalent to the hydrostatic pressure (namely the water column pressure). When calculating the maximum horizontal principal stress, hydrostatic pressure in the fracturing section can be used to represent the pore pressure. Therefore, in this work, hydrostatic pressure is used to replace the pore pressure during the in-situ stress measurements of the Dongzhai Habor area.

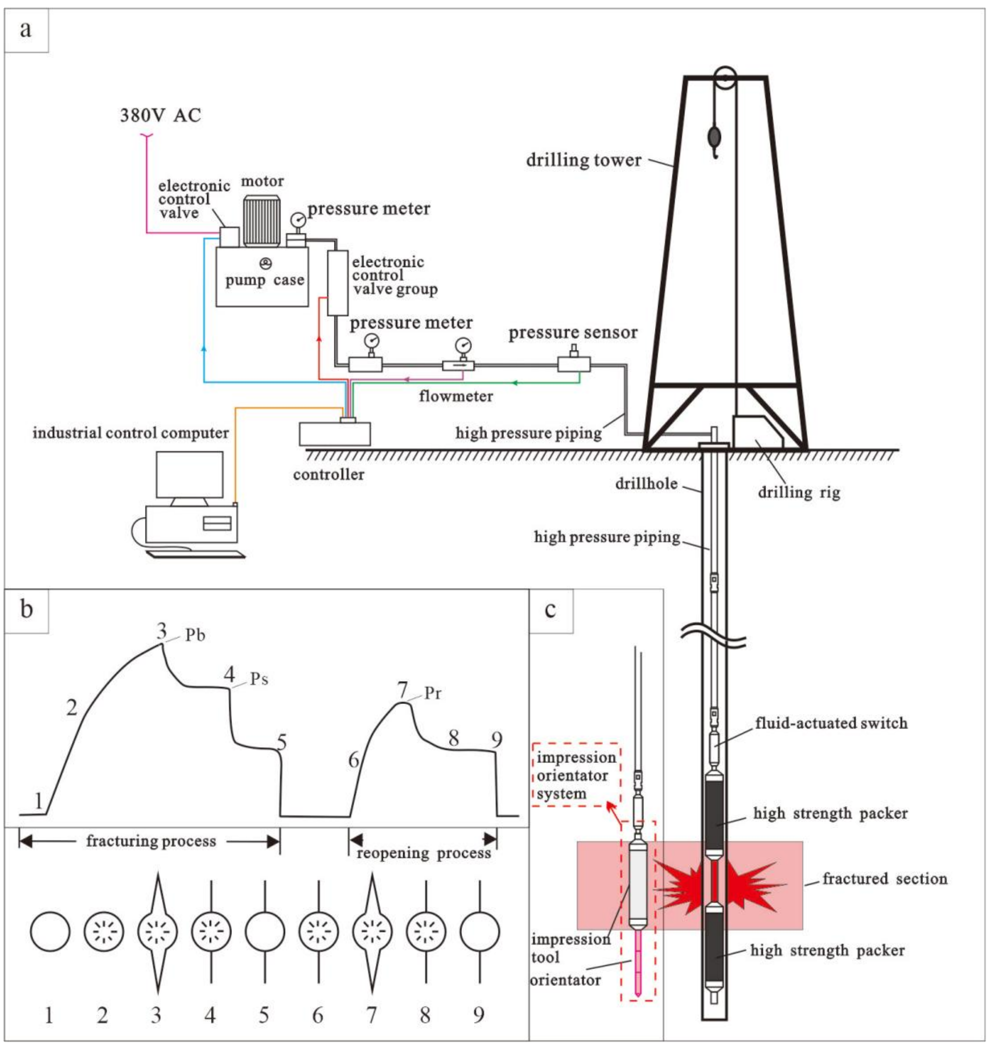

Fig. 3 The hydraulic fracturing geostress measurement system and fracturing process.

4. RESULTS AND ANALYSIS

Following the technological specifications for the in-situ stress measurements by hydraulic fracturing and core releasing method [51], ten hydraulic fracturing tests and four impression orientation tests were undertaken. Through the drafting of the measuring curve of pressure over time, the peak value of fracturing pressure was obvious, with the four cyclic fracturing curves displaying consistency and repeatability, indicating that all of the collected data are reliable and able to be used in the in-situ stress calculations. Determining the direction of the principal compressive stress was undertaken through the impression orientator system at 79.21 m, 101.56 m, 178.19 m, and 281.86 m, with the directions of maximum horizontal principal stress being, respectively, 7.03° NE, 15.36° NW, 75.34° NW, and 33.96° NW (Fig. 4b).

Interpreting the blasting pressure (P_b) and the re-tension pressure (P_r) according to the pressure-time measurement curves, and the instantaneous closing pressure (P_s) according to the dp/dt and dT/dP methods [52-53] used to be interpreted, requires substituting the interpreted fracturing parameters into formulas (2) and (3). According to the different lithologies revealed by the borehole, the natural density of Quaternary clay between depths 0 and 7.93 m is taken to be 2.65 g/cm, and the natural density of granite from the Yanshanian period between 7.93 m to 301.95 m is taken to be 2.70 g/cm. Substituting the above data into formula (4), and the state of the in-situ stress of the Puqian measuring sections can be obtained (Table 1).

Table 1 presents the in-situ stress measurements results applying the hydrofracturing method within the Puqian borehole. The maximum horizontal principal stress (S_H) is between 5.70 and 12.07 MPa, whereas the minimum horizontal principal stress (S_h) is between 4.13 and 8.16 MPa. The direction of the practical measuring maximum horizontal principal stress (fracture orientation) changes from 7.03° NE at a depth of 80 m to 33.96° NW at a depth of 282 m.

Table 1. Measurements of the hydrofracturing in-situ stress in the Puqian borehole

Depth of the Puqian measurement section (m)	Pressure value (MPa)			
	P_b	P_r	P_s	P_0
34.30	9.68	6.35	4.13	0.34
60.90	10.49	6.45	4.35	0.61
79.21	14.03	8.57	7.04	0.79
101.56	14.41	7.95	5.38	1.02
152.56	9.98	7.14	5.96	1.53
178.19	14.25	8.31	6.60	1.78
207.36	11.32	6.51	5.61	2.07
238.86	11.90	8.82	6.90	2.39
266.35	14.99	9.66	7.93	2.66
281.86	12.57	9.59	8.16	2.82

Note: P_b - rock blasting pressure; P_r - rock re-open pressure; P_s - instantaneous closing pump pressure; and P_0 - pore water pressure.

Table 1 (cont.). Measurements of the hydrofracturing in-situ stress in the Puqian borehole

Depth of the Puqian measurement section (m)	**Principal stresses (MPa)**		
	$\boldsymbol{\sigma_H}$	$\boldsymbol{\sigma_h}$	$\boldsymbol{\sigma_v}$
34.30	5.70	4.13	0.93
60.90	5.99	4.35	1.64
79.21	11.76	7.04	2.14
101.56	7.17	5.38	2.74
152.56	9.21	5.96	4.12
178.19	9.71	6.60	4.81
207.36	8.25	5.61	5.60
238.86	9.49	6.90	6.45
266.35	11.47	7.93	7.19
281.86	12.07	8.16	7.61

Note: σ_H - maximum horizontal principal stress; σ_h - minimum horizontal principal stress; and σ_v - vertical principal stress

Table 1 (cont.). Measurements of the hydrofracturing in-situ stress in the Puqian borehole

Depth of the Puqian measurement section (m)	$\boldsymbol{\frac{\sigma_H}{\sigma_v}}$	$\boldsymbol{\frac{\sigma_h}{\sigma_v}}$	$\boldsymbol{\sigma_H}$ **Orientation**
34.30	6.15	4.46	
60.90	3.64	2.65	
79.21	5.50	3.29	7.03° NE
101.56	2.62	1.96	15.36° NW
152.56	2.24	1.45	
178.19	2.02	1.37	75.34° NW
207.36	1.47	1.00	
238.86	1.47	1.07	
266.35	1.59	1.10	
281.86	1.59	1.07	33.96° NW

Note: $\frac{\sigma_H}{\sigma_v}$ - maximum horizontal lateral pressure coefficient; and $\frac{\sigma_h}{\sigma_v}$ - minimum horizontal lateral pressure coefficient.

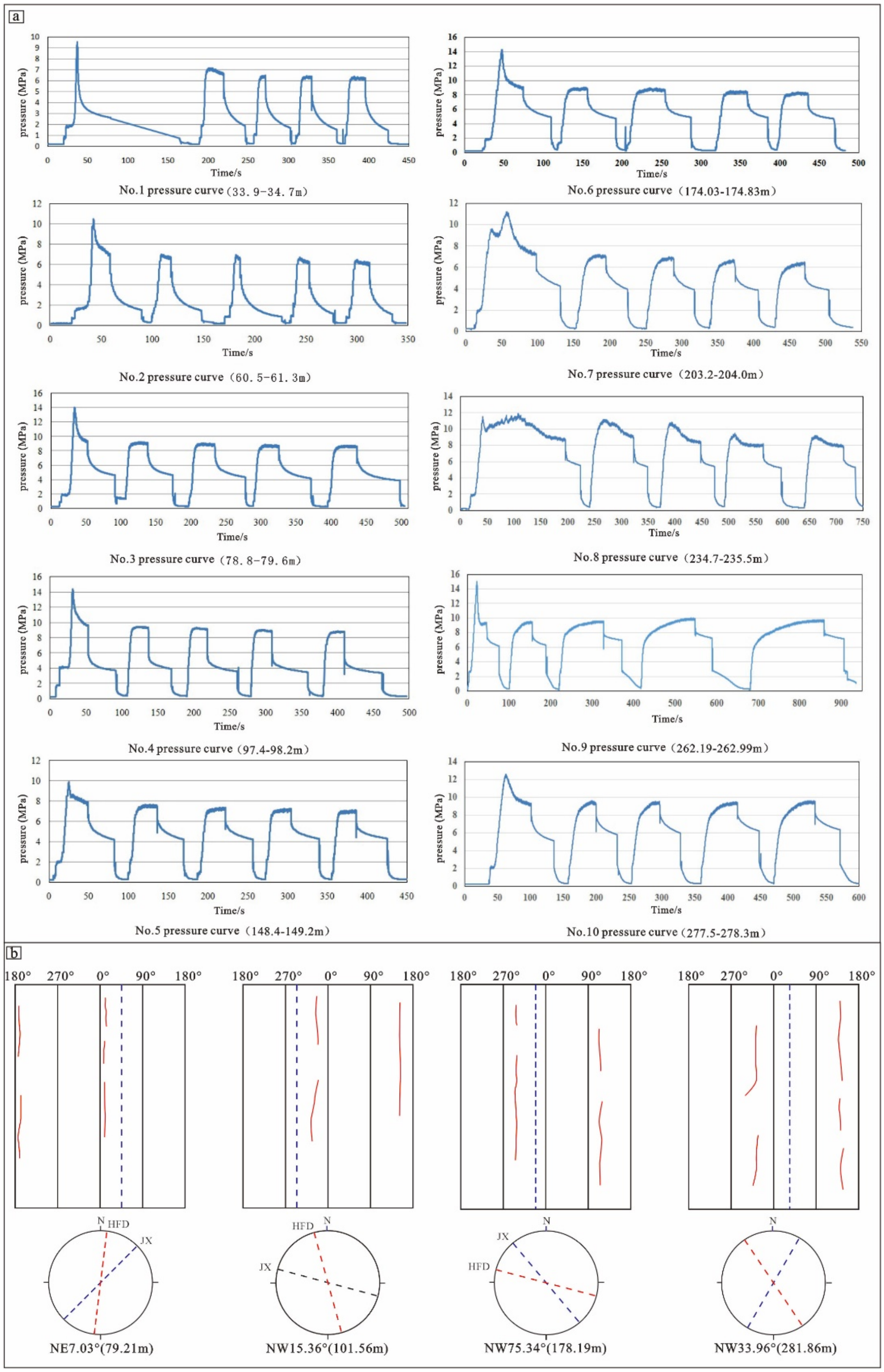

Fig.4. (a) Pressure-time measuring curves and (b) impression orientation results of the in-situ stress measurements in the Puqian borehole.

5. DISCUSSION

5.1. Distribution law of the magnitude of the principal stress changing with depth

Considering the obtained values of principal stress, a regression analysis was carried out to determine the distribution regular of the maximum horizontal principal stress (S_H) and the minimum horizontal principal stress (S_h) and how it changes with depth. Drawing up the pressure change curves and the fitting curves of the principal stress with the depth (Fig. 5), the resulting linear regression relationships are as follows:

$$S_H = 0.0152D + 6.75, \quad R = 0.6718 \tag{5}$$

$$S_h = 0.0146D + 3.78, \quad R = 0.7923 \tag{6}$$

where D is the depth down the borehole, and R is the correlation.

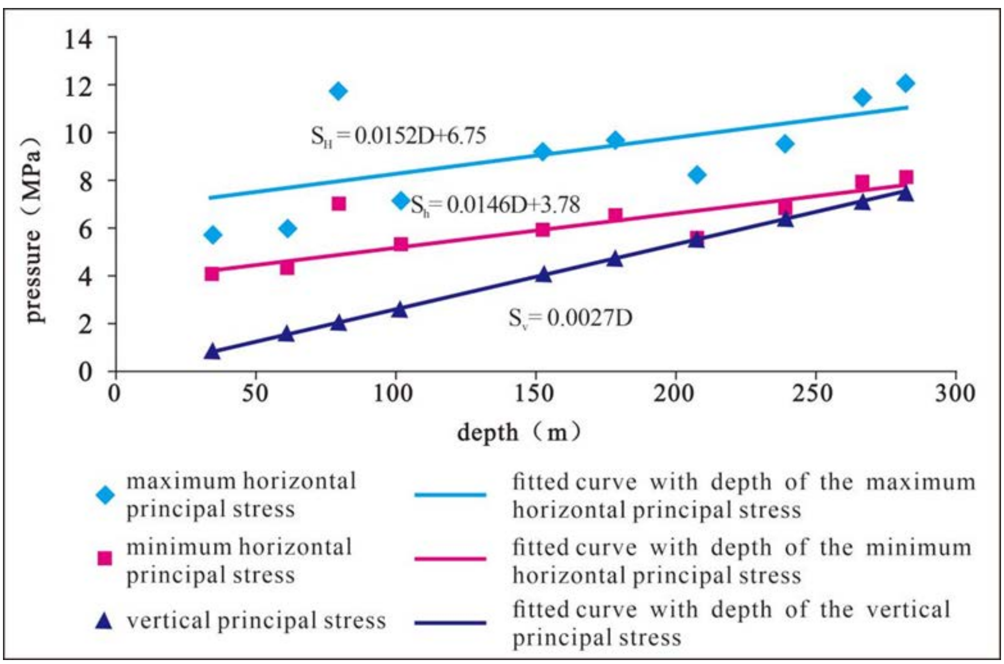

Fig. 5. Principal stresses versus depth in the Puqian borehole.

From Fig. 5, we can suggest that, within the scope of the measured depth, the value of the principal stress is consistent with a linearly increasing trend with increasing depth, and the relationship between the three principal stresses is $S_H > S_h > S_v$. This shows that the shallower segments at this location are dominated by the horizontal principal stress, but what should be noted is that the horizontal principal stress increases suddenly at a depth of 80 m. This is one section which seems out of place with the general trend of the other sections. The results show that the horizontal principal stress is greatly influenced by the structure at the 80m position and presents the phenomenon of uneven distribution and stress concentration. In addition, the slope of the fitted curve of the horizontal principal stress is less than that of the lead principal stress, so it can be suggested that at greater depths, the vertical principal stress value will exceed the minimum horizontal principal stress value, revealing a state of strike-slip stress, and even overcome the maximum horizontal principal stress, revealing a state of positive fault stress.

5.2. The distribution characteristics of in-situ stress

Lateral pressure coefficient is an important parameter to evaluate the level of formation stress field. Domestic and foreign scholars have done a lot of related work and used to judge the level of in-situ stress in the study area (Gonzalez and Hijazo, 2008; Chen et al., 2017; Xu et al., 2016). From Table 1 and Fig. 5, it is obvious that the distribution characteristics of in-situ stress around the Dongzhai Harbor area at present are as follows:

The principal stress increases with a linear trend with increasing depth from 0~280 m, where the relationship between the principal stresses is $S_H > S_h > S_v$. The ratio between the maximum horizontal principal stress σ_H and the vertical principal stress σ_v is between 1.47 ~ 6.15, with an average of 2.83. The ratio between the minimum horizontal principal stress σ_h and the vertical principal stress σ_v is between 1.00 and 4.46, with an average value of 1.94, indicating that the stress field of the shallow part of stratum is dominated by horizontal stress.

The distribution of the principal stress within the measurement range in the Puqian borehole is greatly affected by the local tectonism, and it presents the phenomenon of extremely uneven and stress concentration. Compared with the tectonic stress field in the South China region [3], the principal stress value of the Puqian borehole is moderately above the average level.

The direction of the maximum horizontal principal compressive stress changes from 7.02° NE to 33.96° NW, which indicates that it is controlled by the stress field in the NNE direction over a depth of 80 m, and then in the NW direction from 80 to 300 m depth in this area.

5.3. Fault activity analysis under the present-day geostress field

A judgement of the region's faults' activity based on the results of in-situ stress measurements has been widely used [10], [35], [41] [54-56]. According to the Coulomb friction criteria, when the maximum, minimum, and vertical principal stresses are related by $S_H > S_h > S_v$, $S_H > S_v > S_h$, and $S_v > S_H > S_h$, they are indicative of reverse faults, strike-slip faults, and normal faults, respectively [57].

By using the hydraulic fracturing in-situ stress measurements, the direction of the maximum principal compressive stress in the Dongzhai Harbor area is found to be 33.96° NW, which is about equivalent basically to the direction of the principal compressive stress achieved by focal mechanism solution (45° NW) [58] , indicating that the direction of the principal compressive stress is always in the NW direction, and the current stress field of Dongzhai Harbor has an important influence on the faults activities and their stability.

It can be seen from Fig. 6 that, under the action of the stress field in the NW direction, the Dongzhai Harbor section of the MPF is cut by the branches of the PQF in the NNW and NW directions, and a migration movement toward the NE in the form of a ladder. Through the stress data obtained from the measurements, it appears that the shallow part of the east coast of Dongzhai Harbor is in a state of inverse stress. But the eastern and western branches of the PQF have the characteristics of a positive fault and strike-slip.

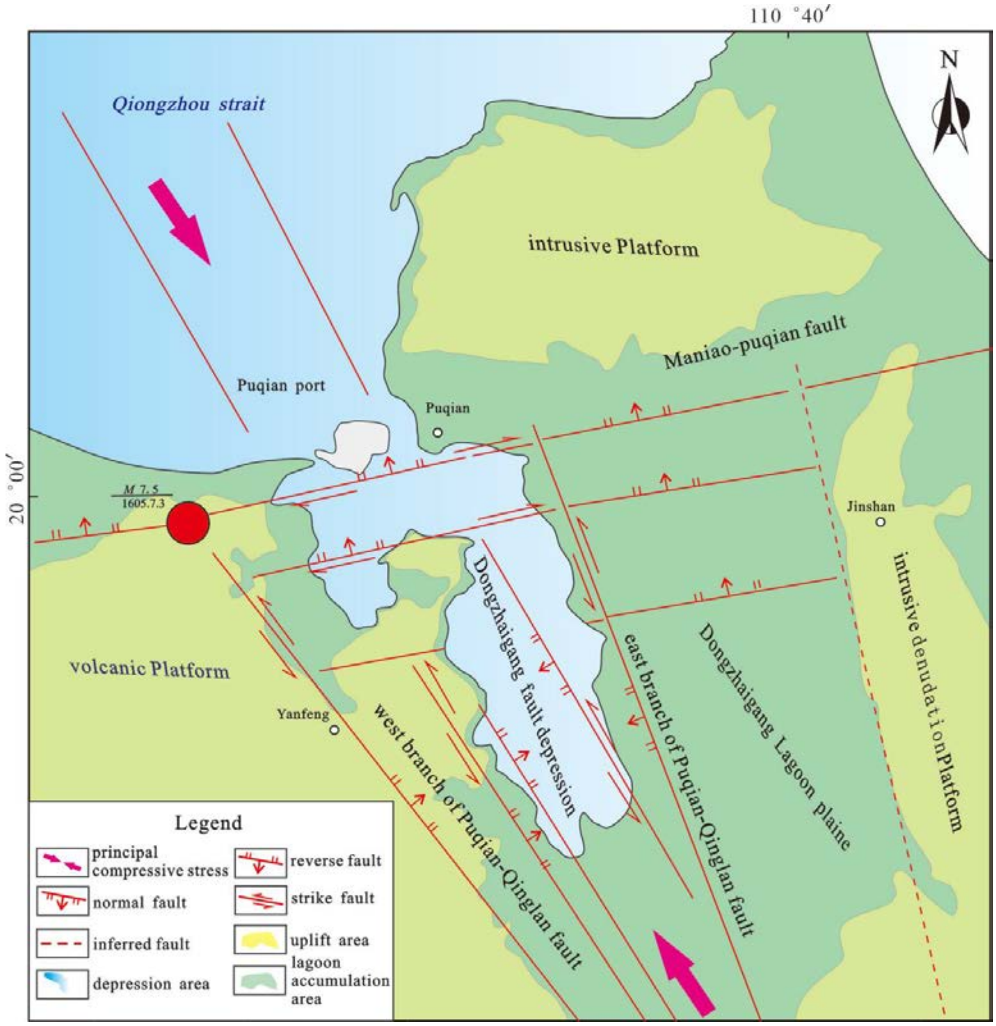

Fig. 6 Sketch map of the geostress field effect on the fault activities in the Dongzhai Harbor area.

5.4. The influence of the NW geostress state on the subsidence of the Dongzhai Harbor graben

Previous studies have shown that Dongzhai Harbor has been continuously sinking since the late Cenozoic era [47]. Some researchers [59-62] believe that the subsidence of Dongzhai Harbor is mainly due to the normal fault activity. Furthermore, Hu and other researchers [63] found that there may be a magma capsule beneath the 15 kilometers depth at the westen of Dongzhai Harbor, with a length of 21 km (EW), and a width of 12 km (SN), exhibiting gradual uplift, with the Dongzhai Harbor subsidence being affected by the differential movement in the vertical direction, thermal activity and upper mantle materials. However, the focal mechanism solution of earthquakes with magnitudes M1.5 to M7.5 in the Northeast Hainan region suggests that the direction of the principle compressive stress is on average 10° NW

[64, 65]. Through the measurement of the direction of principal compressive stress in the shallow stratum (over 280 m depth) of the Dongzhai Harbor region, it was seen that the current stress field in the area is dominated by tectonic stress in the NW direction, but with a trend to rotate towards the NWW direction with depth. Therefore, the action of the NW geostress state is one of the driving sources behind the subsidence of Dongzhai Harbor.

6. CONCLUSIONS

(1) The stress measurements carried out in the Puqian borehole show that the maximum horizontal principal stress ranges between 5.70 and 12.07 MPa, and the minimum horizontal principal stress is from 4.13 to 8.16 MPa in the Dongzhai Harbor area. Compared with the tectonic stress field in the South China region, these values of principal stress are at a moderately upper level.

(2) The relationship among the three principal stress is $S_H > S_h > S_v$ Within a shallow measurement of 280 meters. This shows that the shallow stratum of this locality is dominated by horizontal principal stress, and the principal stress increases with depth.

(3) The principal compressive stress shows a NW trend and is one of the controlling factors of the local fault activity and the sources behind the Dongzhai Harbor graben subsidence.

ACKNOWLEDGMENTS

We are grateful for the guidance of Daogong Hu and Hua Peng and their suggestions concerning the writing of this manuscript, and to Jingchao Gu and Jingwei Hao for the help with the drilling work in the field. We also appreciate the valuable comments and suggestions made by the reviewers, whose efforts are gratefully acknowledged. This study was financially supported by the National Natural Science Foundation of China (No.42272222); China Geological Survey (grant nos. DD20230249; DD20190306, DD20190546, DD20160149); Basic research funds of Institute of Geomechanics, Chinese Academy of Geological Sciences (DZLXJK202106; DZLXJK202211).

REFERENCES

[1] Chen, E.M., Huang, Y.Y. Preliminary discussion on the 1605 Qiongzhou earthquake and its seismogenetic structure. Seismology and Geology, 1979, 1(4): p. 37-44.

[2] Chen, E.M, Huang, Y.Y. Characteristics of the Seismic Damage and Analysis of the Seismic Structure of the 1605 Great Earthquake of Qiongzhou, Hainan Island. Acta Seismologica Sinica, 1989, 11(3): p. 319-331.

[3] Lin, J.Z., Liang, G.Z., Zhao, Y., Xie, M.F. Focal mechanism and tectonic stress field of coastal southeast China. ACTA Seismologica Sinica, 1980, 2(3): p. 245-257.

[4] Li, Z.X., Zhao, W.J., Liu, G.X. A Study on Deep Crust Structures and Stress Situation of the 1605 Qiongshan Strong Earthquake. China Journal of Seismology, 2006, 26(1): p. 28-36.

[5] Chen, Q.C., Fan, T.Y., Li, X.S., He, S.L., Zhang, C.Y. In situ measurements and comprehensive research on the present crustal stress of Northern South China Sea. Chinese J. Geophys, 2014, 57(8): p. 2518-2529.

[6] Li, F.Q. In-situ stress measurement. Chinese Journal Rock Mechanics and Engineering, 1985, 4(1): p. 95-111.

[7] Cai, M.F. Review of principles and methods for rock stress measurement. Chinese Journal Rock Mechanics and Engineering, 1993, 12 (3): 357-388.

[8] Liu, Y F, Liu, Y.K. New advance in 3D geostress measurement by hydraulic fracturing technique in one borehole. Chinese Journal Rock Mechanics and Engineering, 2006, 25(2): p. 3816-3822.

[9] Kang, H.P., Lin, J., Zhang, X. Research and application of in-situ stress measurement in deep mines. Chinese Journal Rock Mechanics and Engineering, 2007, 26(5): p. 929-933.

[10] Peng H., Ma X.M., Jiang J.J., Peng L.G. Research on stress field and hydraulic fracturing in-situ stress measurement of 1000 m deep hole in zhaolou coal mine. Chinese Journal of Rock Mechanics and Engineering, 2011, 30(8): p.1638-1645.

[11] Chen, Q.C., Sun, D.S, Cui, J.J. Hydraulic fracturing stress measurements in Xuefengshan deep borehole and its significance. Journal of Geomechanics, 2019, 25(5): p. 853-865.

[12] Zhao, J., Hefny, A. M., Zhou, Y. X., Hydrofracturing in situ stress measurements in Singapore granite. International Journal of Rock Mechanics & Mining Sciences, 2005, 42: p. 577-583.

[13] Synn, J. H., Park, C., Jung, Y. B., Sunwoo, C., Kim, K. S., Choi, S. Y., Song, M. K., Shin I J., Rutqvist J. Integrated 3-D stress determination by hydraulic fracturing in multiple inclined boreholes beneath an underground cavern. International Journal of Rock Mechanics & Mining Sciences, 2015, 75: p. 44-55.

[14] Damani, A., Sondergeld, C. H., Rai, C S. Experimental investigation of in situ and injection fluid effect on hydraulic fracture mechanism using acoustic emission in Tennessee sandstone. Journal of Petroleum Science and Engineering, 2018, 171: 315-324.

[15] Sesetty V., Ghassemi A. Effect of rock anisotropy on wellbore stresses and hydraulic fracture propagation. International Journal of Rock Mechanics and Mining Sciences, 2018, 112: p. 369-384.

[16] An, Q.M., Ding, L.F., Wang, H.Z. Research of property and activity of longmen mountain fault zone. Crustal Deformation and Earthquake, 2004, 24(2): p.115-119.

[17] Miao, S., Wan, L., Lai, X., Wang, S. Relation analysis between in-situ stress field and geological tectonism in sanshandao gold mine. Chinese Journal of Rock Mechanics and Engineering, 2004, 23(23): p. 3996-3999.

[18] Cai, M. F., Peng, H., Qiao, L., Ma, X. M. Distribution law of in-situ stress field and its relationship to regional geological structures in wanfu coal mine. Journal of China Coal Society, 2008, 33(11): p. 1248-1252.

[19] Peng, H., Ma, X.M., Jiang, J.J. Stability and stress measurement near the qingchuan fault in the northern longmen mountain ns. Journal of Geomechanics, 2009, 15(2): p. 114-130.

[20] Li, B., Guo, Q.L., Wang, J.X., Hu, X.H., Ding, L.F., Xu, J.S. Characteristics of in-situ stress at mengshan fault and its stability analysis. Rock and Soil Mechanics, 2014, 35(2): p. 501-507.

[21] Feng, C.J., Zhang, P., Qi, B.S., Meng, J. Tan, C.X. Recent Tectonic Stress Field at the Shallow Earth's Crust near the Tan-Lu Fault Zone. Geoscience. 2017, 31(1): p. 47-70.

[22] Li, B., Ding, L.F., Wang, J.X., Hou, J.H., Xie, F.R. The state of the in-situ stress and fault stability evaluation of the Penlai Coast. Journal of Geomechanics, 2019, 25(4): p. 459-466.

[23] Wang, C., Song, C., Guo, Q., Mao, J., Zhang, Y. New insights into stress changes before and after the Wenchuan Earthquake using hydraulic fracturing measurements. Engineering Geology, 2015, 194: p. 98-113.

[24] Li, P., Cai, M. F., Guo, Q. F., Ren, F. H., Miao, S. J. Current stress field and its relationship to tectonism in a coal mining district, central China, for underground coal energy exploration. Energy Reports, 2022, 8: p. 5313-5328.

[25] Li, P., Guo, Q. F., Cai, M. F., Miao, S. J. Present-day state of tectonic stress and tectonization in coastal gold mine area near Laizhou Gulf, North China. Trans. Nonferrous Met. Soc. China, 2023, 33: p. 865-888.

[26] Kang, H., Zhang, X., Si, L., Wu, Y., Gao, F. In-situ stress measurements and stress distribution characteristics in underground coal mines in China. Engineering Geology, 2010, 116: p. 333-345.

[27] Kang, H. P., Lv, H. W., Gao, F. Q. Understanding mechanisms of destressing mining-induced stresses using hydraulic fracturing. International Journal of Coal Geology, 2018, 196: p. 19-28.

[28] Liu, Y. Q., Li, H. B., Luo, C. W., Wang, X., In situ stressmeasurements by hydraulic fracturing in theWestern Route of South to NorthWater Transfer Project in China. Engineering Geology, 2014, 168: p. 114-119.

[29] Jo, Y., Chang, C. D., Ji, S. H., Park, K. W. In situ stress states at KURT, an underground research laboratory in South Korea for the study of high-level radioactive waste disposal. Engineering Geology, 2019, 259: p. 105198.

[30] Liu ,J. B., Liu, C. Y., Yao, Q. L., Si, G. Y. The position of hydraulic fracturing to initiate vertical fractures in hard hanging roof for stress relief. International Journal of Rock Mechanics & Mining Sciences, 2020, 132: p.104328.

[31] Zhao, X. G., Wang, J., Qin, X. H., Cai, M., Su, R., He, J G., Zong, Z. H., Ma, L. K., Ji, R. L., Zhang, M., Zhang, S., Yun, L., Chen, Q C., Niu, L. L., An Q M. In-situ stress measurements and regional stress field assessment in the Xinjiang candidate area for China's HLW disposal. Engineering Geology, 2015, 97: p. 42-56.

[32] Du, J. J., Qin, X. H., Zeng, Q. L., Zhang, L Q., Chen, Q C., Zhou, J., Meng, W. Estimation of the present-day stress field using in-situ stress measurements in the Alxa area, Inner Mongolia for China's HLWdisposal. Engineering Geology, 2017, 220: p. 76-84.

[33] Zhang C. Y., Chen Q. C., Qin X. H., Hong B., Meng W., Zhang Q F. In-situ stress and fracture characterization of a candidate repository for spent nuclear fuel in Gansu, northwestern China. Engineering Geology, 2017, 231: p. 218-229.

[34] Xu, H. J., Sang, S. X., Yang, J. F. In-situ stress measurements by hydraulic fracturing and its implication on coalbed methane development in Western Guizhou, SW China. Journal of Unconventional Oil and Gas Resources, 2016, 15: p.1-10.

[35] Qin , X. H., Chen, Q. C., Wu, M. L., Tan, C. C., Feng, C. J., Meng, W. In-situ stress measurements along the Beichuan-Yingxiu fault after the Wenchuan earthquake. Engineering Geology, 2015, 194: p.114-122.

[36] Li, F.Q. Application of in situ stress measurements to the assessment of a site for nuclear waste disposal. Chinese Journal of Rock Mechanics and Engineering, 1993, 12(1): p. 55-62.

[37] Cai, M.F., Chen, C.Z., Peng, H. Ji, H.G., Qiao, L., Tan, Z.Y. In-situ stress measurement by hydraulic fracturing technique in deep position of WANFU coal mine. Chinese Journal Rock Mechanics and Engineering, 2006, 25(5): p. 1069-1074.

[38] M,a X.M., Peng, H., Li, J.S., Li, J.W., Liao, H.Q., Yang, S.X. In-Situ Stress Measurement and Its Application to Rock Burst Analysis in Xinbaiyanzhai Tunnel of the Xiangyu Railway. Acta Geoscientica Sinica, 2006, 27(2)181-186.

[39] Meng, W., Chen, Q. C., Du, J., Feng, C. J., Qin, X. H., An, Q.M. In-situ stress measurement in Singapore. Chinese J. Geophys, 2012, 5(8): p. 2611-2619.

[40] Zhou C.H., Yin J.M., Ding X.L., Ai K. Complex Measurements of Geo-Stress in Deep Diversion Tunnel and Research on Distribution Law of Regional Stress Field in Qinling Mountain. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(plus1): 2956-2964.

[41] Du, J.J., Chen, Q.C., An, Q.M., Wang, Y.F, Meng, W., Li, G.Q. Hydrofracturing in-situ stress Measurement In Hanzhong Basin, Shaanxi Province. Acta Seismologica Sinica, 2013: 35(6): p. 799-808.

[42] Ma, X.M., Peng, H., Li, Z., Jiang, J. Bai, J., Peng, L. In situ stress Measurements by Hydraulic Fracturing Method in The Great Depth Borehole, In: Proceedings of the 6th International Symposium on In-situ Rock Stress. ISRM Specialized Conference, 2013. 2013: p. 986-993.

[43] Niu, L.L., Chen, Q.C., Feng, C.J., Meng, W., He, J.G. In-situ stress measurement of candidate area for high level radioactive waste repository in Xinjiang. Chinese Journal of Rock Mechanics and Engineering, 2017, 36(4): p. 917-927.

[44] Zhao, J., Hefny, A. M., Zhou, Y. X. Hydrofracturing in situ stress measurements in Singapore granite. International Journal of Rock Mechanics & Mining Sciences, 2005, 42: p. 577-583.

[45] Jiang, W.L, Zhang, J.F, Gong, L.X. Interpretation of Multi-source RS Images of Active Fault in the North of Hainan Island. Seismology and Geology, 2007, 29(4): p. 796-804.

[46] Yan, Y.D., Chen, E.M, Huang, Y.Y. Three-Dimensional Photoelastic Simulating Experiments to Tectonics Stress Field of Qiongzhou Great Earthquake of 1605 in Hainan, China. Northwestern Seismological Journal, 1988, 10(2): p. 63-70.

[47] Ding, Y.Y., Zhao, X.T., Hu, D.G., Zhang, X.J., Wang, C.Q., Hu, Z.W., Xia, M.M., Wu, H. You, B.J. Late Cenozoic Fault Activity in Northeastern Hainan Island and Its Controlling Effect on Tectonic Subsidence in Dongzhai Port. Acta Geoscientica Sinica, 2018, 39(2): p. 155-166.

[48] Haimson, B.C. Measurement of in situ stress. Methods Exp Phys, 1987, 24(Part B): p. 377-408.

[49] Haimson, B.C. Hydraulic fracturing stress measurements, special issue. Int JRock Mech Min Sci, 1989, 26: p. 447-685.

[50] Haimson, B.C, Lee, M.Y, Song, L. Shallow hydraulic fracturing measurements in Korea support tectonic and seismic indicators of regional stress. Int J Rock Mech Min Sci, 2003, 40: p.1243-56.

[51] CSB (China Seismological Bureau). Technical specification for in-situ stress measurement of hydraulic fracturing and core lifting method (DB/T14-2000). 2001.

[52] Feng, C., Chen, Q., Wu, M., Zhao, J., Li, G. Analysis of hydraulic fracturing stress measurement data—discussion of methods frequently used to determine instantaneous shut-in pressure. Rock and Soil Mechanics, 2012, 33(7): pp.2149-2159.

[53] Feng, C., Zhang, P., Qin, X., Meng, W., Tan, C., Chen, Q. Near-surface stress measurements in the longmenshan fault belt after the 2008 wenchuan ms8.0 earthquake. International Journal of Rock Mechanics & Mining Sciences, 2015, 77: p. 358-377.

[54] Meng, W., Chen, Q. C., Du, J., Feng, C.J., Qin, X.H., An, Q.M. In-situ stress measurement in Singapore. Chinese J. Geophys, 2012, 5(8): p. 2611-2619.

[55] Zhao, J., Hefny, A. M., Zhou, Y. X., Hydrofracturing in situ stress measurements in Singapore granite. International Journal of Rock Mechanics & Mining Sciences, 2005, 42: p.577-583.

[56] Wang, C., Song, C., Guo, Q., Mao, J., Zhang, Y. New insights into stress changes before and after the Wenchuan Earthquake using hydraulic fracturing measurements. Engineering Geology, 2015, 194: p. 98-113.

[57] Li, F.Q. Fault activity and original stress state. Seismic Geology and Seismological Committee of Chinese Seismological Society. Study on active faults in China. Beijing: Earthquake Publishers, 1994, p.15-21.

[58] Zhan, W.H., Liu, Y.X. A Study on Faulting and Regional Stability in Qiongzhou Strait. Tropic Oceanology, 1989, 8(4): p. 70-77.

[59] Xu, Q.H. Discussion on subsidence mechanism of Qiongshan earthquake. South China Journal of Seismology, 1985, (4): 33-40.

[60] Xu, Q.H. Recent sinking in the Dongzhai Harbor area, northern Qiongzhou. Marine Sciences, 1986, 10(1): p. 24-28.

[61] Xu, Q.H. An understanding of seismic geology in LeiQiong Depression. South China Journal of Seismology, 1986, (1): p. 86-96.

[62] Xu, Q.H. Subsidence Caused by the Qiongzhou Large Earthquake in 1605 and the Formation and Vicissitude of Dongzhaigang Bay on Hainan Island. Earthquake Research in China, 1990, 4(1): 71-82.

[63] Hu, J.C., Bai, D.H., Wang, W.H., Lin, Z., Xiang, X.P., Wang, L. Magnetotelluric surveying and electrical structure of the deep underground part in Leiqiong volcanic area. Acta Seismologica Sinica, 2007, 29(3): 258-264.

[64] Zhang, H.N., Zhao, X.T. Characteristics of the neotectonic movement in the Hainan island and Leizhou Peninsula area. Scientia Geologica Sinica, 1984, 3: p. 276-287.

[65] Zhang, H.N., Zhang, F.L., Wu, Z.L. Seismicity and seismic structure of the Hainan island. Earthquake Research in China, 1985, 1(3): p. 59-63.