Study on Structural Plane of Deep Rock Mass in Xinchang Preferred Site for Underground Research Laboratory on Geological Disposal of High-Level Radioactive Waste in China

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Abstract. Structural plane is an important influence factor for the rock mass quality, 3D modelling, borehole hydraulic test and engineering design of underground research laboratory. Xinchang rock mass in Beishan area of Gansu province has been confirmed the preferred site for URL on geological disposal of high-level radioactive waste in China. The characteristics of structural plane in Xinchang rock mass are obtained based on acoustic borehole televiewer and other geological information. The results indicate that the granite rock mass with a high integrity is beneficial for construction of URL. The width of faults around preferred site and incidence in horizontal and vertical decrease as the depth increases. Characteristics of dip and strike of structural plane is the same as other structure in this area. All research results provide meaning information for design of URL and further geological research.

Keywords: Acoustic borehole televiewer; structural plane; deep rock mass; Xinchang; preferred Site.

1. Introduction
With the development of nuclear power, the disposal of high-level radioactive waste (HLW) becomes an important issue for nuclear safety and environment protection in worldwide [1-3]. As a technically feasible and safe way to dispose HLW, deep geological disposal is internationally accepted. The facility which is located in 300~1000m underground for disposal of HLW is named HLW repository [4-5], and there is no HLW repository built up to now.

According to the overall planning for geological disposal programme, the strategy for HLW disposal can be divided into three typical stages: site selection for underground research laboratory (URL) and HLW repository; URL construction and in-situ tests; repository construction and operation. The URL plays a role of “bridge” among the three stages. In order to assess and demonstrate the long-term performance and safety of the HLW repository, more than twenty URLs have been constructed in the world in the past few decades and a lot of researches and tests have been conducted in them. As the geological barrier, the suitability of host rock, such as granite, clay and salt rocks, is one of the most important parts in whole disposal barrier system. Structural plane of host rock is an important influence factor for host rock mass quality, 3D modeling, borehole hydraulic test and engineering design of URL and must be investigated clearly during site selection for URL.
Based on drill-core, the numbers and types of fillings of structural planes of deep host rock can be directly obtained, but the depth, orientation, especially the dip direction cannot. Therefore, characteristics of structural planes cannot be fully evaluated \[6\]. As a geophysical logging tool with small diameter, the measurement accuracy and logging speed of acoustic borehole televiewer (ATV) are greatly improved because of applying advanced acoustic beam focusing technology, digital recording technology, and digital data processing technology. Compared with primitive logging tool, ATV shows advantages, for example, characteristics of structural planes of deep host rock can be intuitively and clearly displayed in the form of amplitude images, the magnetic coordinates of borehole wall are recorded and oriented accurately, dip of structural plane is corrected, and the minimum resolution can achieve 0.5 mm in the lateral and vertical directions. Based on the advantages, ATV has been widely used in geology, hydrogeology, exploration and design, and engineering investigation \[7-9\].

Xinchang granite rock mass in Beishan area of Gansu province has been confirmed the preferred site for URL on geological disposal of HLW in China. Many boreholes with depth of 600m were drilled in and around Xinchang site during the stage of site selection. The borehole BS32 located in the center of the site is vertical, and its purpose is to verify the integrality of host rock mass. The boreholes BS37 and BS39 with tilt/azimuth of 11°/110° and 9°/120° located in the edge of the site are inclined and the purpose is to verify characteristics of linear structure around the site. The distribution of boreholes mentioned above basically covers all the site range. Therefore, characteristics of structural planes obtained through boreholes can be used to comprehensively represent the characteristics of structural planes of host rock mass of the preferred site. A series of investigations based on the data obtained by ATV logging in BS32, BS37 and BS39 and other geological results have been conducted, including density, occurrence, and width of structural plane, integrity and other characteristics of rock mass, to assess the suitability of host rock mass for URL.

2. Geological Setting
Xinchang granite rock mass locates about 80km north of Yumen City, with length of 17km and width of 5km, and the main lithology comprise Xinchang monzonitic granite(O1\text{x}), Ji Jinggou granodiorite(O1\text{j}), Yuan Yanggou gneissic monzonitic granite(Pt 22\text{y}) and Hong Liujing gneissic granodiorite (Pt 22\text{h}) (Fig. 1). Gneissic monzonitic granite and gneissic granodiorite distributed east-westwards mainly locate in the northern and southern edges of the rock mass, while monzonitic granite and granodiorite locate in the central, western and northern parts of the rock mass \[10\]. Geological research results show that two types of faults were developed in Xinchang, transpressional fault and tensile-shearing fault \[11\]. The transpressional faults developed in Mesozoic and previous strata, with length of 10km to 20km and width of n*10m, are boundary faults of Xinchang rock mass, strike nearly E-W. The tensile-shearing faults are dominantly developed in rock mass, with length of about 2km to 5km and dips of 50°to 80°, strike NE and NW, characterized by left-lateral slip. The preferred site for URL is located in central part of Xinchang granite rock mass, and host rocks are monzonitic granite and granodiorite. The main faults around the site are F31, F32, F33, F34 and F32-2 (Fig.1). Characteristics of the occurrence, scale, mechanical properties and tectonite of faults mentioned above are investigated and researched in detail based on interpretation of remote sensing images, field investigation and trial trench exploration. The specific content is shown in Table 1.

3. Imaging Principles and Composition of Acoustic Borehole Televiewer
Imaging principle of acoustic borehole televiewer is shown in Fig.2. The high-frequency ultrasonic beam generated and emitted by centralized ultrasonic transducer is transmitted through groundwater, reflected off the borehole wall, and returned. Travel time and amplitude are recorded. Travel time increases if borehole radius is marked by borehole breakthroughs, open aperture fractures, faults, or karsts caves. Meanwhile, the magnetometer records and orients the magnetic coordinates of the borehole wall, the inclinometer records and corrects the tilt of structural plane. Finally, amplitude image of
reflected pulse presented as an unwrapped, rectangular color-scale image showing characteristics of structural planes and borehole wall is formed.

![Geological Sketch Map](image1)

**Fig. 1.** Geological sketch map of preferred site for URL

![Sensor Structure](image2)

**Fig. 2.** Structure of sensor and principle of ATV

The acoustic borehole televiewer used in research is produced by Mount Sopris Instruments Inc., USA, and included probes, data collectors, winches and displays. The probe model is QL40, emit acoustic beam with frequency of 1.2 MHz, is suitable for borehole with diameter of 50mm to 510mm. The magnetometer has a resolution of 0.5° and 1° in dip and dip direction. The maximum measuring depth is 1500 m.
### Table 1. Characteristics of faults around preferred site for URL

| Fault No. | length /km | occurrence | Mechanical property          | Characteristics                                                                 |
|-----------|------------|------------|------------------------------|---------------------------------------------------------------------------------|
| F31       | 5.5        | 290°~305° ∠70°~83° | sinistral tensile-shearing | The width of fault zone is 1.0m to 2.6 m, and fault zone consists of single or more than two roughly parallel fault planes. Host rock shows characteristics of silicified breccia and silicate alteration. The early lamprophyre penetrates faults zone. |
| F32       | 6.1        | 260°~290° ∠60°~80° | sinistral tensile-shearing | The fault zone is 0.3m to 3.1m wide and consists of single or more than two roughly parallel fault planes. The types of tectonite are tectonic breccia (including silicified breccia), cataclastic rock and monzonitic granites. The early monzonitic granites and lamprophyre penetrate the fault. |
| F32-2     | 3.2        | 56° ∠50°~55° | tensile | A less than 100m-wide alteration zone, strikes 146°, shows albition and limonite alterations. |
| F33       | 5.1        | 280°~300° ∠68°~75° | sinistral tensile-shearing | The fault zone consists of one or more roughly parallel fault planes. Single fault plane is generally 0.45m to 0.60m wide, and the maximum width is 4.0m. The tectonites are silicified breccia, cataclastic rock, and fragmentized granodiorite and granite dike. |
| F34       | 4.6        | 310°~320° ∠72°~86° | tensile | The fault zone is 0.2m to 0.9m wide and consists of a large number of silicified breccia and a small amount of cataclastic rock. |

#### 4. Data Acquisition and Image Processing

Data acquisition of acoustic borehole televiwer is automatically controlled by MSlog™ software. The relative parameters can be adjusted according to variations in downhole condition when the ATV probe is lowered, to obtain optimal visual images. Data logging starts when probe starts upward from the borehole bottom. The measurement speed is maintained at 1.2 to 1.5m/min to ensure the accuracy of the collected data and image.

Image processing and interpreting were performed using Well CAD™ software which can use to: (1) convert the amplitude into 2D image of borehole wall,(2) orient the drill core,(3) automatically repair partial missing data,(4) restore the 2D borehole wall image into 3D histogram,(5) automatically calculate occurrence of structural plane and draw strike roses and polar projection,(6)correct raw dips and dip directions of structural planes to true ones,(7) generate new diagram,(8) achieve mutual conversion for various image formats.

Raw data files are imported into the Well CAD™ software, to automatically obtain amplitude image of whole borehole wall which is presented as an image orientated to progress N-E-S-W-N from left to right. Reflection intensities of different substances have different performances; Hence, the colors and patterns of amplitude image of structural planes, caves and host rock are different obviously. Structural planes are presented in the form of a sine/cosine curve in amplitude image and contrast sharply with the image of host rock.

Occurrence of structural plane can be obtained by measuring sine or cosine curve, the method is to create a new image layer with the same size on the amplitude image of borehole wall, and then accurately depict the sine/cosine curve on the new image layer and form an image of structural planes distribution with depth of borehole. The depth, dip and dip direction of each structural plane calculated automatically by Well CAD™ software can be output numerically or represented in the form of "tadpole" symbol. The interval where "tadpole" located represents dip of structural plane, while the orientation of "tadpole tail" represents dip direction of structural plane, and strike direction is perpendicular to dip direction. (Fig.3).
Note that drilling-induced fractures are also common in many boreholes and will affect the analysis results, and must be removed when interpreted, in order to ensure the accuracy of data.

Fig. 3. ATV image of structural planes distribution with depth

5. Characteristics Analysis of Structural Planes
Interval (or density) and sets of structural planes are important factor influencing the integrity of the rock mass. According to structural plane data after comparative interpretation, statistical analysis and research on intensive fractured zone of rock mass, fault zone and fracture density are carried out.

5.1. characteristics of intensive fractured zone
There are different division standards for interval of structural planes of rock mass in different industries. In this paper, the sections with fracture density≥10m⁻¹ (fracture interval≤10cm) and width≥30cm are classified as intensive fractured zone, considering the possible impact produced by structural planes on the construction of URL. The statistical data of intensive fractured zone in BS32, BS37 and BS39 are shown in Table 2.

| Borehole No. | Measuring range /m | Intensive fractured zone | Amount | Distribution range /m | Accumulative length/m | Proportion /% |
|-------------|-------------------|-------------------------|--------|----------------------|-----------------------|--------------|
| BS32        | 19.50-601.60      |                         | 2      | 44.80-46.04 and 111.54-112.23 | 1.93                  | 0.33         |
| BS37        | 25.50-622.0       |                         | 3      | 53.63-54.87,616.55-617.40 and 618.55-620.22 | 3.76                  | 0.63         |
| BS39        | 18.50-602.80      |                         | 10     | 107.26-107.89,121.16-121.58,143.67-145.08,182.58-183.36,187.11-187.82,226.42-227.64,384.22-386.65,464.80-466.23,467.15-470.99 and 473.86-480.76 | 19.77                  | 3.38         |
(1) characteristics of intensive fractured zones in BS32.

The intensive fractured zones developed in BS32 are two sections, with accumulative length of 1.93m, and occupy 0.33% of total length of measuring range. Geological research results indicate that the lithology of intensive fractured zone at 44.80m to 46.04m is granodiorite in which developed single steep long fracture. On the other hand, the strength becomes weak because of alterations, the granodiorite was easily broken. While the lithology of intensive fractured zone at the 111.54m to 112.23m is granodiorite also, in which developed a group of nearly parallel fractures with average occurrence of $156^\circ \pm 44^\circ$ (Fig.4).

![Fig.4. Intensive fractured zone located 111.54~112.23m in BS32 and polar projection](image)

(2) characteristics of intensive fractured zones in BS37.

The intensive fractured zones developed in BS37 are three sections, with accumulative length of 3.76m, occupy 0.63% of total length of measuring range. The interpretation results and geological data show that the lithology of intensive fractured zone at 53.63m to 54.87m is granodiorite, in which developed two sets of fractures intersecting each other. Average occurrence of gentle fracture is $156^\circ \pm 44^\circ$. A set of steep fractures developed respectively at 616.55m to 617.40m and 618.55m to 620.22m, are filled with calcite. The average occurrences are $310^\circ \pm 73^\circ$ and $307^\circ \pm 67^\circ$ (Fig.5).

![Fig.5. Intensive fractured zone located 618.55~620.22 m in BS37 and polar projection](image)
(3) characteristics of intensive fractured zones in BS39.

There are ten intensive fractured zones developed in BS39, the accumulative length is 19.77m and occupies 3.38% of total length of measuring range. Interpretation results and geological data show that the alteration in intensive fractured zones in BS39 is stronger, compared to that in BS32 and BS37, and the scale is large also. Occurrence of intensive fractured zones at 384.22m to 386.65m is $216^\circ \angle 74^\circ$, while occurrence of other intensive fractured zones is approximately $300^\circ$ to $320^\circ \angle 60^\circ$ to $70^\circ$ (Figure 6).

![Intensive fractured zone located 121.16~121.58m in BS39 and polar projection](image)

**Fig.6.** Intensive fractured zone located 121.16~121.58m in BS39 and polar projection

5.2. characteristics of faults

Drill core shows that BS37 and BS39 respectively pass through fault F34 and F33. Characteristics of deep fault are as follows.

(1) Fault core of F34 is cataclasite with siliceous cement, located 601.70m to 601.98m, and the apparent thickness is about 0.28m while the true thickness is 0.12m, and the occurrence is $297^\circ \angle 64^\circ$ (Fig.7).

![Fault zone located 601.39~602.26m in BS37](image)

**Fig.7.** Fault zone located 601.39~602.26m in BS37
(2) The fault core of F33 is tectonic breccias, located 471.26 to 473.53 m. The apparent thickness is 1.46 m and true thickness is about 0.66 m, and occurrence is 293° ± 63°, which is basically the same as occurrence of 300° ± 73° obtained from surface.

Fig. 8. Fault zone located 471.26–473.53 m in BS39 and polar projection

5.3. characteristics of fracture density
Compared with intensive fractured zone, faults and other large-scale structural planes, single fracture has a weaker effect on integrity of rock mass, however, some steep and large-scale fractures not only affect the quality classification of rock mass, but also is an important factor affecting the permeability of rock mass [12]. Fractures distribute non-uniformly in rock mass and impacts on integrity of rock mass are different also. In order to visually demonstrate the effect of fractures on integrity of rock mass, fracture density is introduced in this paper, namely, number of fracture in the unit length range is used to evaluate integrity of rock mass.

The calculated results show that fracture density of rock mass is extremely low, after removing the data of intensive fractured zone and fault zone. The fracture density in BS32 is the smallest, only 0.26 m⁻¹, while that in BS39 is the largest, reaches 1.84 m⁻¹, and that in BS37 is 0.44 m⁻¹. Results of fracture density indicate that integrity of rock mass is very high. However, the full-hole fracture density has limitations on evaluation of rock mass integrity; in other words, it is difficult to determine intensive sections which may have a great impact on permeability of rock mass and mechanical excavation. Based on this consideration, a further statistical analysis of fracture density of rock mass was carried out. Interval length (12.40 m) of hydraulic tests by using double packer test equipment as a reference is used to count fracture density. Results in Fig. 9 show that differences in fracture density at different depths are obvious.

(1) The borehole section with the highest fracture density in BS32 is located 115.79 to 128.16 m, and the number is 2.02 m⁻¹, while the fracture densities of 91.79 to 104.16 m and 103.79 to 116.16 m are also larger. In the middle and lower parts of BS32, fracture densities are very small, especially below 400.0 m, almost no fracture.

(2) Fracture densities of the upper and bottom parts of BS37 are relatively large, the maximum is 4.01 m⁻¹, located 568.21 to 580.67 m, while those of middle parts are very small. The fracture densities of sections which affected by the intensive fractured zone are obviously larger than that of other sections.

(3) The maximum of fracture density in BS39 is 6.26 m⁻¹, located 457.42 to 469.89 m. It is similar to borehole BS37, the fracture densities of sections affected by fault zone and intensive fractured zone are relatively large.
5.4. occurrence of fracture
Structural plane plays an important role in inverting and verifying regional tectonic stress field. Dips and dip directions of fractures were conducted at 10° and 30° interval, respectively (Fig.10). Results show that the dips of fractures are dominated by steep angles, and the main distribution range is 40° to 80°. while dip directions are different, distributed from 150° to 180° in BS32, and from 270° to 330° in BS37 and BS39.
Dips™ software was used to draw rose diagram and polar projection of fractures diagram (Fig. 11), the results show that occurrence of dominant fractures in BS32 are $158^\circ \pm 45^\circ$ and $307^\circ \pm 69^\circ$, while those in BS37 and BS39 are $309^\circ \pm 69^\circ$ and $299^\circ \pm 60^\circ$, which are basically the same as the occurrence of faults F34 and F33. Characteristics of occurrence of fracture indicate that formation of fractures developed in preferred site is related to the surrounding faults. The strikes of fractures show NNE-NE, which is consistent with the direction of maximum horizontal principal stress measured in borehole around the site [13], and further prove characteristics of the regional tectonic stress field [14,15].

Fig. 11. Rose diagram and polar projection of fractures in BS32,BS37,BS39
5.5. **differences of structural plane characteristics**

As can be seen from research results of structural plane characteristics, there are significant differences in characteristics of deep structural planes obtained in BS32, BS37 and BS39.

1) BS32 does not pass through the fault and demonstrates the ground geological survey and geophysical survey results. Characteristics of structural planes in BS32 show that the middle part of Xinchang granite rock mass has a good integrity and has not been destroyed by the tectonic movement. While BS37 and BS39 expose existence of faults F34 and F33, the occurrences of faults obtained by ATV displays smoothly, and the change of occurrence is small from surface to deep, but the width of fault zone decrease with depth.

2) Consistency of occurrences of dominant fractures indicates that fractures are formed in the same tectonic movement. However, the distributions and occurrence characteristics of intensive fractured zone indicate that formation of intensive fractured zones around the rock mass is related to faults, and the intensive fractured zone in the middle of the rock mass is not.

3) Numbers and spatial distribution of faults, intensive fractured zone and fractures in BS32, BS37 and BS39 have differences. The intensive fractured zone and fractures in the middle of the rock mass are mainly distributed in upper parts and the number is small, especially below 400m, only a small amount of fractures is developed. However, due to the existence of faults and extension in vertical (beyond 400m), intensive fractured zone and fractures around the rock mass are well developed, and the number and density are far greater than those in the middle of the rock mass.

5.6. **effect of structural planes on integrity of rock mass**

As mentioned above, the faults F31, F32, F33 and F34 around the preferred site are tensile-shearing faults. The width of fault zone gradually decreases from north to south and from shallow to deep. For example, the width of fault F33 at 460m is about 0.66m, while only intact cataclasite with siliceous cement can be seen in fault F34 at 590m, on other words, the extension in vertical of fault F34 is limited. Considering that dips of faults is steep and the change is small (about 10°), it can be inferred that the faults have little effect on integrity of rock mass in vertical.

The intensive fractured zones near the faults are generally larger, and occurrences of dominant fractures, including intensive fractured zone, are consistent with that of fault. These characteristics show that the development of the intensive fractured zone is significantly affected by the faults. The influenced width of fault in shallow surfaces is up to 10m, and in deep is about 5m in horizontal.

The intensive fractured zones, including fractures, in the center of the preferred site have a small number and size, and were produced by two sets of fractures intersecting each other or single steep fracture. The dominant fractures in BS32 strike NE, which is consistent with regional tectonic stress field and strike of faults, and the dip direction is SE, which is opposite to those of faults and intensive fractured zones. Characteristics of occurrences of fractures indicate that the central area of the preferred site is not affected by faults, or the effect is limited.

Based on above research results, it can be determined that Xinchang granite rock mass for URL has a very good integrity, with characteristics of few structural planes and small scale. The faults developed around the site do not affect the integrity of central rock mass.

6. **Conclusion**

Acoustic borehole televiewer and other geological information were conducted in Xinchang rock mass confirmed the preferred site for URL on geological disposal of HLW in China, to obtain the characteristics of structural plane, and to assess the integrity and suitability of host rock mass for construction of URL. The results indicate:

1) Xinchang granite rock mass in preferred site has a good integrity and is beneficial for construction of URL.

2) The vertical extension range of fault around the site is limited. Both the scale of fault zones and influenced width in horizontal gradually decrease as the depth increases. The intensive fractured zones were mainly developed around the faults.
(3) The dominant fractures strike NE, which is consistent with regional tectonic stress field.
(4) Research results of structural planes provide important data for 3D modeling, rock mass quality evaluation, design and construction of URL.

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References
[1] Wang Ju, Chen Weiming, Su Rui, et al. Geological disposal of high-level radioactive waste and its key scientific issues[J], Chinese Journal of Rock Mechanics and Engineering, 2006, 25(4), pp.801-812.
[2] Zhang Huazhu. Geological disposal of high level radioactive waste in China: present situation and perspectives[J], Uranium Geology, 2004, 20(4), pp.193-195.
[3] Yi Shuping, Ma Haiyi, Zheng Chunmiao. Advances in Research on Disposal of Radioactive Waste [J], Acta Geoscientica Sinica, 2011, 32(5), pp.592-600.
[4] Pan Ziqiang, Qian Qihu. Strategic research for deep geological disposal of high-level radioactive waste [M]. Beijing: Atomic Energy Press, 2009, pp.3-4.
[5] Wang J. High-level radioactive waste disposal in China: update 2010 [J]. Journal of Rock Mechanics and Geotechnical Engineering, 2010, 2(1): 1-11.
[6] Wang Xiyong, Su Rui, Chen Liang, et al. Study on structural plane characteristics of deep rock mass based on acoustic borehole TV[J], World Nuclear Geoscience, 2014, 31(1), pp.31-44.
[7] Mao Jizhen, Ultrasonic imaging borehole TV and its application to rock engineering [J], Chinese Journal of Rock Mechanics and Engineering, 1994, 13(3), pp.247-260.
[8] Su Rui, Zong Zihua, Wang Ju. Acoustic borehole televiewer with high-resolution and its application to deep formation for geological disposal of nuclear waste[J], Chinese Journal of Rock Mechanics and Engineering, 2005, 24(16), p.2922-2928.
[9] Wang Chuanying, LAW K Tim. Review of borehole camera technology[J], Chinese Journal of Rock Mechanics and Engineering, 2005, 24(19), pp.3440-3448.
[10] Jin Yuanxin, Min Maozhong, Chen Weiming, et al. Study on granite characteristics of Xinchang section of candidate Beishan area, Gansu Province [J], Chinese Journal of Rock Mechanics and Engineering, 2007, 26(supplement 2), pp.3974-3981.
[11] Guo Zhaojie, Zhang Zhicheng, Zhang Chen, et al. Lateral growth of the Altyn Tagh strike-slip fault at the north margin of the Qinghai—Tibet Plateau: Late Cenozoic strike-slip faults and the crustal stability in the Beishan area, Gansu, China [J], Geological Bulletin of China, 2007, 27(10), pp.1678-1686.
[12] Ji Ruili, Zhang Ming, Zhou Zhichao. Research on In-situ Hydraulic Test Method in Beishan Pre-selected Area [J], Uranium Geology, 2018, 34(1), pp.53-59.
[13] Zhao Xingguang, Wang Ju, Ma Like, et al. Distribution characteristics of geostress field in xinchang rock block of candidate beishan area for high level radioactive waste repository in china [J], Chinese Journal of Rock Mechanics and Engineering, 2014, 33(2), pp.3750-3757.
[14] Xie Furen, Chen Qunze, Cui Xiaofeng, et al. Fundamental database of crustal stress environment in continental China[J], Progress in Geophysics, 2007, 22(1), pp.131-136.
[15] Niu Zhijun, Wang Min, Sun Hanrong, et al. Recent observation result of the present crustal movement velocity field in mainland China[J], Chinese Science Bulletin, 2005, 50(8), pp.839-840.