Recent temporal changes in the stress state and fault reactivation assessment of HTB underground gas storage in China associated with gas injection and extraction

Guiyun Gao1,2*, Chandong Chang2, Chenghu Wang1, Jin Jia3

1 Key Laboratory of Crustal Dynamics, National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing 100085, China
2 Department of Geological Sciences, Chungnam National University, Daejeon, 34134, South Korea
3 Xi’an Research Institute Co. Ltd, China Coal Technology and Engineering Group Corp., Xi’an 710077, China

*Corresponding author. E-mail address: guiyungao@nimh.ac.cn, ORCID: 0000-0003-2769-8907

Abstract. The stress state variations due to seasonal injection and extraction of gas in HTB underground gas storage (HTB-UGS) were estimated, as well as the fault-slip analysis of the main fault, to understand how gas injection and extraction result in earthquakes. The stress state at different depths at the time of a complete depletion in 2012 was first estimated using image-logged borehole breakout data and stress inversions of focal mechanism solutions. Further, the temporal variations of the stress state caused by changes in the pore pressure due to gas injection and extraction were estimated based on a simple pore pressure–stress coupling assumption. The fault reactivation/slip tendency temporal changes and their possible relation with seismicity in this area were analyzed. Results revealed that the stress orientation in the reservoir layer was around N21°E–N23°E, which was consistent with the tectonic stress prevailing direction. The stress regime varied between reverse and strike-slip faulting stress regimes during the gas injection and extraction cycles. The main fault-slip tendency initially decreased continuously with gas production and then increased with gas injection. Earthquake sequences appeared when the slip tendency increased to a critical value of 0.45 ± 0.03.

Keywords: Underground gas storage (UGS); Induced seismicity; Stress state; Slip tendency; Borehole breakout

1. Introduction

Storing oil or gas underground can help address seasonal shortages and the need to balance the supply-demand chain of energy requirements due to its high safety factor, minimal floor space requirement, lower installation, and operating costs [1–3]. China has built 27 underground gas storage (UGS) facilities thus far. Currently, the largest UGS facility in China is the HTB underground gas storage (HTB-UGS), located in Xinjiang Province. It has a maximum gas storage capacity of 10.7 billion m³ and an effective gas storage capacity of 4.5 billion m³, which is roughly three times Xinjiang’s overall gas production [4]. The HTB-UGS facility was constructed in a depleted gas field of the Petro China Xinjiang Oilfield Branch, which produced gas and oil for approximately 14 years from 1998 to 2012 [5]. In this facility, natural gas is injected into the reservoir in warm seasons and extracted for supply in cold seasons. The HTB-UGS had completed eight injection–extraction cycles as of April 2021.
However, the seasonal injection and extraction of gas from UGS sites typically cause changes in cyclic pore pressure and caprock displacements. This seasonal injection and extraction of gas could reactivate existing faults and induce or activate seismicity [6–8]. For example, earthquakes with magnitudes as high as $M_r 3.7$ were caused by the extraction of natural gas from the shallow deposits in the Roswinkel and Bergermeer fields in the Netherlands [9]. Gan and Frohlich [10] noted that earthquakes with magnitudes exceeding 3 may have been induced or triggered by gas injection in the Cogdell oil field in Texas in the United States. The Castor UGS in Spain, where the earthquake reached a magnitude $M_o 4.3$, is another interesting case of seismicity correlated with gas injection operations [11]. The potential impact of HTB-UGS operations on local seismicity in this area has always been a major concern because the site is adjacent to a seismically active region, which is the northern Tien Shan tectonic belt [12, 13]. Almost no earthquakes with magnitudes greater than 2 occurred within 10 km radius of this site before the HTB-UGS operation. However, earthquake swarms were recorded shortly after the injection of gas in the first two operation cycles, including two earthquakes with magnitudes greater than 3 [8]. These findings suggest that most of the detected earthquakes from 2013 to 2015 were induced by the HTB-UGS operations [4, 14, 15].

Further, the mechanism through which gas injection and extraction can induce earthquakes remains unclear and debatable [16, 17]. The pore pressure increase due to gas injection and causes fault slips by reducing the effective normal stress on the fault plane, thereby inducing seismicity [6, 18]. In addition, poroelastic stress variations in surrounding media can induce faulting [19]. Fault stability is controlled by pre-existing and poroelastic stress variations caused by changes in the pore pressure [20]. Thus, the assessment of fault stability due to the pore pressure changes is a key factor in understanding induced seismicity. However, knowledge about reservoir stress conditions and fault friction is limited, which are pivotal parameters for understanding fault mechanisms. Slip tendency analysis is a method for assessing a fault’s stress states and related potential reactivation [21]. Here the fault-slip potential is characterized using shear stress to effective normal stress ratio. If the stress changes during the injection and extraction of gas/oil are constrained, the fault stability and induced seismicity can be analyzed.

The major goal of this study is to estimate the changes in stress state and fault-slip tendency caused by gas injection and extraction within the HTB-UGS reservoir. The estimations are vital to understanding fault stability and induced seismicity. Image-logged wellbore breakouts in a borehole and other mechanical parameters were used to constrain the orientations and magnitudes of the stress state at the HTB-UGS reservoir depth (3.5–3.7 km). Then, the stress state variations over time, which were caused by changes in the pore pressure induced by petroleum production and other HTB-UGS operations were estimated based on the simple assumption of coupling between horizontal stresses and pore pressure. The slip tendency variations for the main fault and their possible relationship with seismicity in the area were discussed. This study is expected to provide a new perspective for understanding induced seismicity.

2. Tectonic setting

The HTB-UGS, which is adjacent to the northern Tien Shan Mountains, is located in the southern Junggar foreland sub-basin in northwestern China, 4.5 km from Hutubi County, in Xinjiang Province (figure 1). The regional topography reveals several subparallel and east–west thrust-fold belts, formed by the active uplifting of the Tien Shan Mountains since the Cenozoic Indo-Asian collision. A north–south crustal shortening is occurring at a rate of 2.5–6.2 mm/year, according to calculations using global positioning system data [22]. This phenomenon underscores the coupling effect of the Junggar Basin and northern Tien Shan block.

The overall HTB-UGS structure is a fault-nose type trap with a distance of approximately 12.8 km along the E–W fold axis and a width of 7.8 km along the N–S direction (figure 1, yellow area) [23]. Three faults break through the reservoir formation in the vicinity of the HTB-UGS. In general, these three faults tend to strike along the NW–SE direction, dip toward the south and lie parallel to one another (figure 1).
3. Recent stress state in the HTB-UGS region before the operation

3.1. Stress orientation

Stress inversions were conducted using the STRESSINVERSE code [24], which was used to obtain the prevailing stress orientation based on focal mechanism solutions of 11 earthquakes (M ≥ 3.0) that occurred in the study area before the gas injection (figure 1). According to the fault-type classification suggested by Zoback [25], six, three, and two of these earthquakes were of the reverse, strike-slip, and normal faulting types, respectively. The stress inversion results showed that the maximum principal stress (S1) direction was near N21°E (figure 2). The minimum principal stress (S3) dip deviated roughly 30° from the vertical direction and was closest to this direction among the three principal stresses, indicating that the stress state favored the reverse-faulting stress regime.

The stress orientation was estimated using borehole breakouts (BOs) detected in a vertical borehole (Hu001). BOs were continuously detected from 3,458 to 3,768 m in the reservoir rock (figure 3) based on Schlumberger’s formation microimager logs (Cao, 2013). Figure 3 shows that two pairs of opposed BOs exhibited nearly constant azimuth angles throughout the vertical hole’s measured length, with averages of 113° ± 6° and 293° ± 7° in the reservoir layer. Therefore, the overall orientation of the maximum horizontal principal stress (S1) was along NNE (N23°E ± 6°), which was consistent with the maximum principal stress (S1) orientation obtained from the focal mechanism solution’s stress inversion.
3.2. Stress magnitude estimation

Stress indicators, such as BOs and drilling-induced tensile fractures (DITFs) were used to estimate the stress magnitudes. Based on the stress distribution around a circular hole in a rock mass with given far-field principal stress, the circumferential effective principal stress, $\sigma_{\theta\theta}$, acting on the circular borehole wall in a vertical borehole can be expressed as [26]:

$$
\sigma_{\theta\theta} = S_h + 2(S_h - S_v)\cos 2\theta - P - P_m
$$

where $P_m$ is the borehole pressure and $\theta$ is the azimuth angle from the $S_h$ direction. The breakouts occur when $\sigma_{\theta\theta}$ exceeds the effective compressive strength, $C_{eff}$, of the borehole wall rocks. For critical analysis, the $\sigma_{\theta\theta}$ is assumed to reach the maximum value, $\sigma_{\theta\theta}^{max}$, at the margins of the breakouts, which is equal to $C_{eff}$. Meanwhile, $2\theta$ in Eq. is equal to the breakout width, $W_{BO}$. Conversely, DITFs occur in vertical wells when the minimum $\sigma_{\theta\theta}$, $\sigma_{\theta\theta}^{min}$ ($\theta = 90^\circ$ or $270^\circ$), at the wellbore wall overcomes the surrounding rock’s tensile strength. Then, the stress amplitude can be constrained using the BO widths and the DITFs occurrence when the pore pressure, borehole pressure, and rock strength parameters are available.

The modified Wiebols–Cook criterion, proposed by Wiebols and Cook [27] and modified by Zhou [28], was adopted in this study to define the compressive strength. This criterion employs only two rock properties: uniaxial compressive strength, UCS and internal friction coefficient, $\mu_i$. And their typical values are depicted in figure 4. Vertical stress, $S_v$, was calculated from the overburden. The magnitude of the minimum horizontal principal stress, $S_h$, was estimated based on the borehole techniques in the literature [29, 30]. The findings were relatively consistent in the reservoir layer, and no DITFs or hydraulic fractures were observed (figure 3). Thus, the lowest horizontal principal stress was higher than the borehole pressure. In such cases, the stress magnitude ranges could be constrained using the BOs and DITFs combined with compressive strength (figure 4). Large BOs without DITFs were observed at 3,604-m depth, and the possible $S_h$ and $S_i$ ranges were extremely well-constrained within the shaded area in figure 4. The $S_i$ and $S_h$ ranges were 131.3–149.4 MPa and 71.8–76.0 MPa, respectively.

The stress magnitudes at different depths were estimated using the same stress-constrained method. Figure 5 summarizes the constrained in situ stress profiles at all analyzed depths in the HTB-UGS.
the reservoir layer, the magnitudes of $S_{H}$ and $S_{h}$ tended to increase minimally alongside depth, with the former exhibiting a considerable increase at the boundary between the upper caprock and reservoir. The $S_{h}$ range was less than that of $S_{v}$, whereas the $S_{H}$ range was predominantly higher than that of $S_{v}$, indicating that the stress state in the depleted reservoir in 2012 was in a strike-slip faulting stress regime.

![Figure 4. Stress constraint enacted by BOs and DITF criterion that encompasses possible $S_{H}$ and $S_{h}$ magnitudes for the given $S_{v}$ range at a depth of 3,604 m in 2012.](image)

**Figure 4.** Stress constraint enacted by BOs and DITF criterion that encompasses possible $S_{H}$ and $S_{h}$ magnitudes for the given $S_{v}$ range at a depth of 3,604 m in 2012.

**Figure 5.** Constrained stress profile in caprock and reservoir layer of HTB-UGS.

4. Recent temporal changes in stress magnitude due to extraction and injection of gas

Poroelastic theory, which predicts the magnitude of stress changes based on gas extraction and injection of the reservoir, was used in this study to acquire insights into changes in stress over time [31]. The pore pressures during petroleum production and HTB-UGS operation were measured and estimated based on the wellhead pressures [4, 14, 15] (figure 6). Pore pressure–stress coupling analysis (figure 6) was used to estimate horizontal stresses, $S_{H}$ and $S_{h}$, during gas production and UGS operation. The mean $S_{H}$ and $S_{h}$ decreased by roughly 13.3 MPa with petroleum production, whereas $S_{v}$ remained the same from 1998 to 2012. A reverse-faulting stress regime was observed in the reservoir layer before production began in 1998; gas production altered the stress state in the reservoir layer. The initial reverse-faulting stress regime before production switched to a strike-slip faulting stress regime when the minimum stress decreased to below the $S_{v}$ (roughly in 2003) due to a decrease in the pore pressure during petroleum production. Nevertheless, the estimated $S_{H}$ and $S_{h}$ values increased with gas injection and decreased with the gas extraction during the HTB-UGS operation due to the pore pressure changes. Thus, the stress state switched between a strike-slip faulting regime and a reverse-faulting stress regime during the HTB-UGS operation.

![Figure 6. Estimated pore pressure based on wellhead pressure from Zhou](image)
5. Slip tendency and seismicity

The slip susceptibility of the main fault in the HTB-UGS could be analyzed based on the slip tendency analysis after the amplitudes and orientations of the three principal stresses were obtained. The slip tendency \( T_s \), defined as the ratio of shear stress, \( \tau \), to effective normal stress \( (\sigma_n - P) \) on the fault plane [21], is given as

\[
T_s = \frac{\tau}{(\sigma_n - P)}
\]

Slip tendency solely depends on the ratios of principal stresses and the fault surface orientation. The effective normal stress, \( \sigma_n - P \), and shear stress, \( \tau \), on faults can be calculated using the coordinate transformation approach based on the three principal stresses previously estimated. As principal stresses vary with changes in pore pressure, the slip tendency value, \( T_s \), would evolve as pore pressure changes.

The slip tendencies of the main fault (strike = 300°, dip = 42°) during petroleum production and HTB-UGS operation were calculated based on the previously estimated stresses. Figure 7a shows the slip tendency variation from 1998 to 2017. The slip tendency declined gradually with time before 2012, similar to the pore pressure changes, similarly with pore pressure change, indicating that gas production lowered the possibility of fault slip. The calculated slip tendency showed some degree of uncertainty (at an order of about 0.05) mainly due to the uncertainty in stress and pore pressure. If the middle values in the given range of uncertainty were chosen, the slip tendency reached its lowest value at about 0.36 ± 0.03 when the reservoir was depleted in 2012. During the UGS operation period in 2013–2017, the \( T_s \) value fluctuated between 0.35 and 0.52.

The slip tendency value represents the fault activation susceptibility, which is related to earthquake occurrences. The slip tendency changes with variations in the cumulative number and amplitude of seismic events in the study region (figure 7b and c). The first earthquake swarm occurred roughly two months after the injection on August 03, 2013 (figure 7c). The slip tendency value increased to 0.45 during this period. The second earthquake swarm occurred shortly after the start of the second injection in April 2014, as indicated by the sudden increase in the cumulative seismic number. In
addition, the critical slip tendency for this swarm’s occurrence was 0.45. The third and fourth earthquake swarms occurred when the injection began and the $T_s$ values reached 0.46 and 0.45, respectively. If a critical earthquake magnitude of $M$ 1.5 was assumed as an earthquake swarm occurrence indicator, then the critical value of $T_s$ for earthquake swarm occurrence could be 0.45. Stable faults would have a slip tendency below the frictional coefficient’s lower limit, indicating their inability to slip until the slip tendency is high enough to trigger faults slipping. From this perspective, the frictional coefficient of the main fault may be approximately 0.45.

6. Conclusions
This study systematically investigated the changes in stress state and fault-slip susceptibility due to pore pressure changes, to analyze the seismicity induced in this region during petroleum production and HTB-UGS operation (gas injection and extraction). The main conclusions are as follows:
(1) The estimated orientation of the maximum horizontal principal stress based on BO data and stress inversion of focal mechanism solutions was along the N21E°–N23E° direction in the reservoir layer. The result was consistent with the region’s tectonic stress state.
(2) The stress amplitudes constrained using image-logged wellbore breakouts increased slightly alongside depth in the reservoir layer. The horizontal principal stresses decreased with the pore pressure during petroleum production due to pore pressure–stress coupling interaction. The horizontal principal stress increased with the gas injection and decreased with gas extraction during the HTB-UGS operation.
(3) The stress regime initially favored reverse faulting before petroleum production but switched to a strike-slip faulting stress regime during production. Gas injection and extraction from 2013 altered the stress regime in favor of reverse faulting, and vice versa.
(4) The pore pressure declined with the production of gas/oil, resulting in changes in effective stress and a decrease in slip tendency. However, once the gas was injected after June 2013, the slip tendency increased to a critical value where fault slips and earthquake swarms occurred. A critical $T_s$ value of 0.45 ± 0.03 was estimated based on the comparisons between the slip tendency and seismic events from June 2013 to April 2017. The result can be considered as the frictional coefficient of the main fault.

This study analyzed the possible causes of induced seismicity in the HTB-UGS reservoir by estimating the temporal changes in the stress state and fault-slip tendency due to gas injection and extraction; the result offers a new perspective. As this study’s main objective is to estimate the stress state and fault-slip tendency within the reservoir using a relatively simple poroelastic model, the detailed physical mechanisms of earthquakes are not investigated. In addition, the mechanism of induced earthquakes is complicated. A comprehensive investigation covering geomechanical modeling and downhole pressure measurements must effectively understand changes in a stress state, fault stability, and induced seismicity in future work.

7. References
[1] Li Z, Xue Y, Liang J, Qiu D, Su M and Kong F 2020 B. Eng. Geol. Environ. 79 3635-48
[2] Bai M, Shen A, Meng L, Zhu J and Song K 2018 J. Petrol. Sci. Eng. 171 584-91
[3] Ning Zx, Xue Yg, Su Mx, Qiu Dh, Zhang K, Li Zq and Liu Ym 2021 Environ. Earth Sci. 80
[4] Jiang G, Qiao X, Wang X, Lu R, Liu L, Yang H, Su Y, Song L, Wang B and Wong T-f 2020 Earth Planet. Sci. Lett. 530 115943
[5] Pang J, Qian G, Wang B, Yang Z, Wei Y and Li Y 2012 Nat. Gas Ind. 32 83-5
[6] Ellsworth WL 2013 Science 341 12259421-7
[7] McGarr A, Simpson D, Seeber L and Lee W 2002 Int. Geophys. 81 647-64
[8] Science China Earth Sciences Yang H, Liu Y, Wei M, Zhuang J and Zhou S 2017 Sci. China Earth Sci. 60 1632-44
[9] Van Eck T, Goutbeeck F, Haak H and Dost B 2006 Eng. Geol. 87 105-21
[10] Gan W and Frohlich C 2013 Proc. Natl. Acad. Sci. 110 18786-91
[11] Cesca S, Grigoli F, Heimann S, González A, Buforn E, Maghsoudi S, Blanch E and Dahm T 2014 Geophys. J. Int. 198 941-53
[12] Lu R, He D, Xu X, Wang X, Tan X and Wu X 2017 Seismol. Res. Lett. 89 13-21
[13] Deng Q, Zhang P, Xu X, Yang X, Peng S and Feng X 1996 J Geophys Res: Sol Ea 101 5895-920
[14] Tang L, Lu Z, Zhang M, Sun L and Wen L 2018 J Geophys Res: Sol Ea 123 5929-44
[15] Zhou P, Yang H, Wang B and Zhuang J 2019 J Geophys Res: Sol Ea 124 8753-70
[16] Elsworth D, Spiers CJ and Niemeijer AR 2016 Science 354 1380
[17] Li Z, Elsworth D, Wang C and Collab EGS 2021 Nat. Commun. 12 1528
[18] Wang C, Elsworth D, Fang Y and Zhang F 2020 J. Rock Mech. Geotech. 12 720-31
[19] Segall P 1992 Pure Appl. Geophys. 139 535-60
[20] Segall P, Grasso JR and Mossop A 1994 J Geophys Res: Sol Ea 99 15423-38
[21] Morris A, Ferrill DA and Henderson DB 1996 Geology 24 275-8
[22] Burchfiel B, Brown E, Deng Q, Feng X, Li J, Molnar P, Shi J, Wu Z and You H 1999 Int. Geol. Rev. 41 665-700
[23] Wang J, Ge H, Wang X, Liu T, Liu D, Zhang Y and Wu S 2018 Earthq. Res. China 32 288-300
[24] Vavryčuk V 2014 Geophys. J. Int. 199 69-77
[25] Zoback ML 1992 J Geophys Res: Sol Ea 97 11761-82
[26] Jaeger JC, Cook NG and Zimmerman R 2009: John Wiley & Sons.
[27] Wiebols G and Cook N 1968 Int. J. Rock Mech. Min. Geomech. Abstr. 5 529-49
[28] Zhou S 1994 Comput. Geosci. 20 1143-60
[29] Cao X 2013 A research on reservoir geomechanics features of a gas storage in Xinjiang after natural depletion. Beijing: China University of Geoscience
[30] Li M, Li Z and Liao J 2005 Xinjiang Geology 23 29-32
[31] Engelder T and Fischer MP 1994 Geology 22 949-52

Acknowledgments
This work was supported by the Fundamental Research Fund for State Level Scientific Institutes from National Institute of Natural Hazards, MEMC (No. ZDJ2020-07) and the National Natural Science Foundation of China (41574088, 41704096). Guiyun Gao was financially supported by the National Research Foundation of Korea (NRF) during her visit at the Chungnam National University. The authors appreciate assistance by Yanyong Li (Earthquake Agency of Xinjiang Uygur Autonomous Region) for focal mechanism solutions. The authors would like to thank Enago (https://www.enago.cn) for the English language review.