Faults reactivation risk evaluation during water injection into shale gas reservoirs: A case study

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ABSTRACT: Hydraulic fracturing is an effective technique for shale gas development, which breaks tight shale by injecting a large amount of fracturing fluid under high pressure. The potential impacts of hydraulic fracturing on the surrounding environments (such as hydraulic fracturing induced earthquakes) have aroused extensive attentions. Hence it is necessary to study on the evolution rules of reservoir in-situ stress and fault stability during the water injection process of hydraulic fracturing.

In this work, a three-dimensional geomechanical model of a shale gas reservoir which located in Southwestern China is established firstly; Based on the in-situ stress field, numerical simulations on the influence of local in-situ stress and fault stability during quasi-dynamic and dynamic water injection are made. With the calculated shear strain distribution, a workflow for evaluating the seismic moment response in the fault region during water injection is proposed.

Keywords: shale gas, geomechanics, pore pressure, in-situ stress field, fault stability.

1 INTRODUCTION

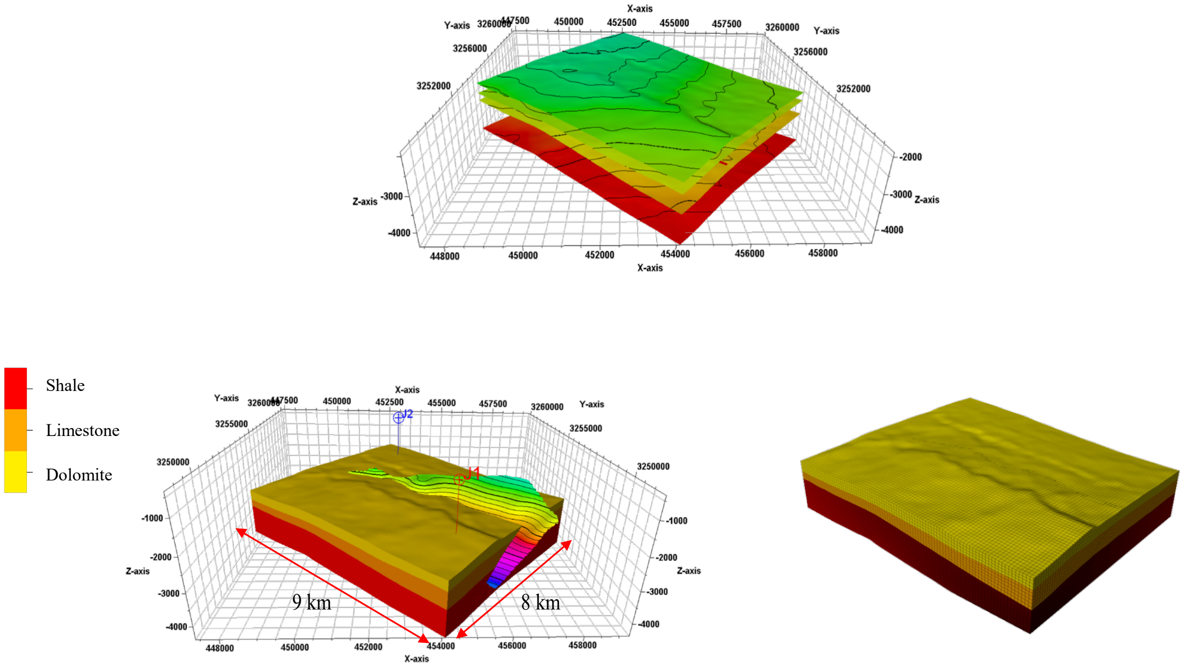
Hydraulic fracturing (HF) is an effective technique for shale gas development, which breaks tight shale by injecting a large amount of fracturing fluid under high pressure. The potential impacts of HF on the surrounding environments (such as HF induced earthquakes) have aroused extensive attentions. The mechanisms of fault activation caused by HF mainly includes pore pressure diffusion and pore elastic stress transmission (Ellsworth et al., 2013). Scuderi et al. (2016) conducted an indoor water injection test at centimeter scale, and the results show that aseismic slide induced by pore pressure diffusion can activate the sliding of the fault in the non-pressurized faults. Similar conclusion can also be found in Barros et al. (2018) indoor experiments at ten meters scale. Through in-situ and indoor water injection tests and numerical simulation studies that the friction properties of the fault change with fluid injection, and the shear stress of the fault increases with the propagation of seismic sliding, which ultimately induces seismic sliding in the non-pressurized area of the fault (Cappa et al., 2015, 2019). Through the research on the 2016 Alberta earthquake of magnitude WM4.1 induced by hydraulic fracturing in Canada, confirmed that the seismic sliding in the area affected by pore pressure diffusion of the fault on a kilometer scale can activate the seismic sliding in the non-pressurized area at the far end of the fault (Eyre et al., 2019).

At present, studying the reservoir local stress field disturbance caused by water injection and the stability law of adjacent faults, most of the calculation models are established only by generalizing the actual formation into a plane, and the elastic parameters of each lithological formation and the distribution of the geo-stress field are predefined. Few researches are focusing on three-dimensional geomechanical model based on the actual structure, geological conditions and fault distribution, and the research on the fault stability caused by water injection in hydraulic fracturing is rare.

2 PHYSICAL MODEL

The reservoir is in southwestern China. To reasonably depict the stress field of the reservoir and analyze the fault stability during water injection, a three-dimensional geomechanical simulation was conducted for the reservoir with the study area about 72 square kilometers. The geological model of the reservoir is about 8 km long in the northeast direction and about 9 km long in the northwest direction, with a buried depth of 3000 m in average.

Figure 1 is the geomechanical model of the reservoir in the study area. The three tectonic surfaces are shown in Figure 1(a), and the three lithological formations are dolomite formation, limestone formation and shale formation from top to bottom accordingly (Figure 1(b)). Furthermore, one fault with the dip angle ranges from 4 ° to 64 ° crossed the studying reservoir, and the spatial distribution is obtained from the seismic interpretation data.



(b) Physical model (c) Finite element mesh

Figure 1. Three-dimensional geomechanical model of the reservoir.

Figure 1(c) is the finite element mesh for this model. The finite element mesh resolution is 100 m in horizontal direction and 5 m in vertical direction. The strain boundary condition is adopted here, and the tectonic strain coefficient is validated with in-situ logging and hydraulic fracturing data. The initial pore pressure is calculated based on the wells sonic data. The vertical stress is derived according to the detected rock density.

3 RESULTS AND DISCUSSION

3.1 Geo-stress distribution

Geo-stress distribution is the key input stress information for hydraulic fracturing and new well design. Based on the numerical simulation, the maximum and minimum horizontal stresses distribution of each formation is shown in Figure 2. As for each formation, the vertical average value of each element is used. The average maximum horizontal stress of each formation is: 55.81 MPa for Dolomite formation, 63.98 MPa for Limestone formation, and 82.24 MPa for shale formation. The average minimum horizontal stress of each formation is: 51.56 MPa for Dolomite formation, 59.43MPa for Limestone formation, and 74.88MPa for shale formation. In general, the horizontal stress increases gradually in line with the burial depth. For each formation, the horizontal stress increases gradually from the northern region to the southern region.

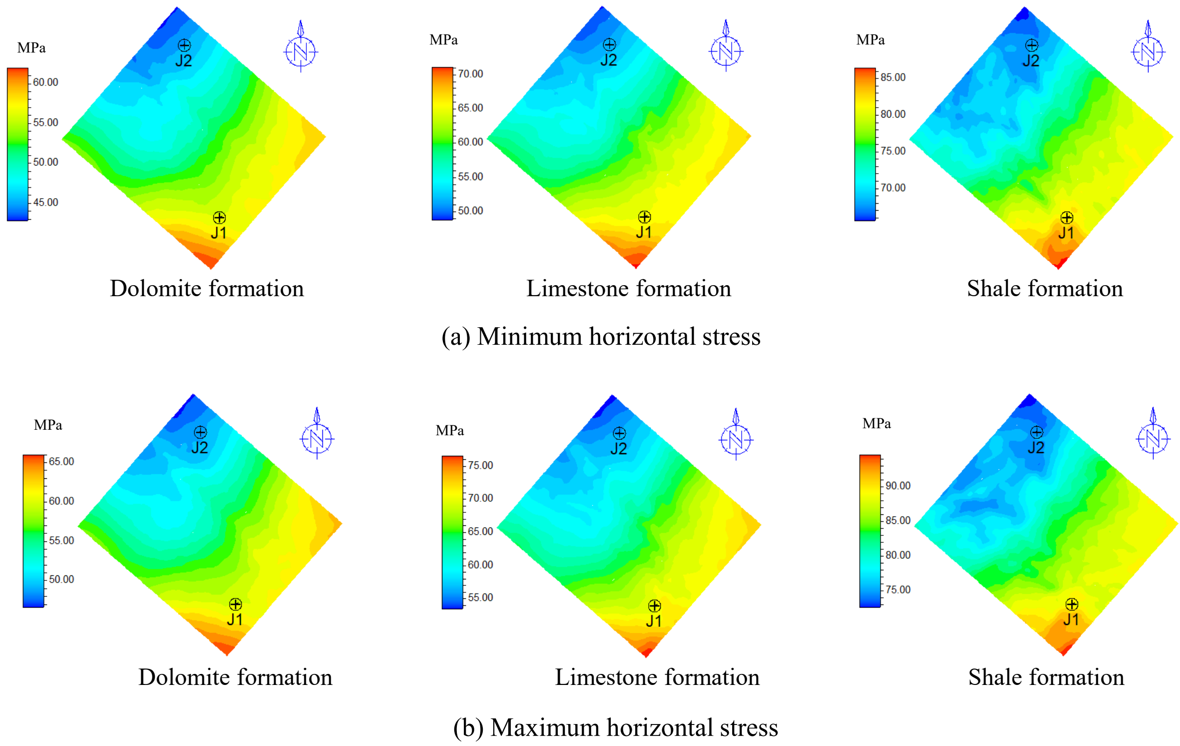


Figure 2. Geo-stress distribution of each formation.

3.2 Fault stability analysis

Faults stability during hydraulic fracturing or water injection is causing attention due to the impacts on surrounding environment. In this work, a workflow for faults stability evaluation is proposed based on the geomechanical results. The calculation process of fault activation risk is shown in Figure 3. The input data include the shear strain of fault element, the geometrical information of the fault and rock mechanical parameters. Then the seismic moment can be calculated by the following equation:

$$M_0 = A\mu d \tag{1}$$

where A is the area of the fault reactivation region, μ is the shear modulus of the rock, and d is the sliding displacement of the fault.

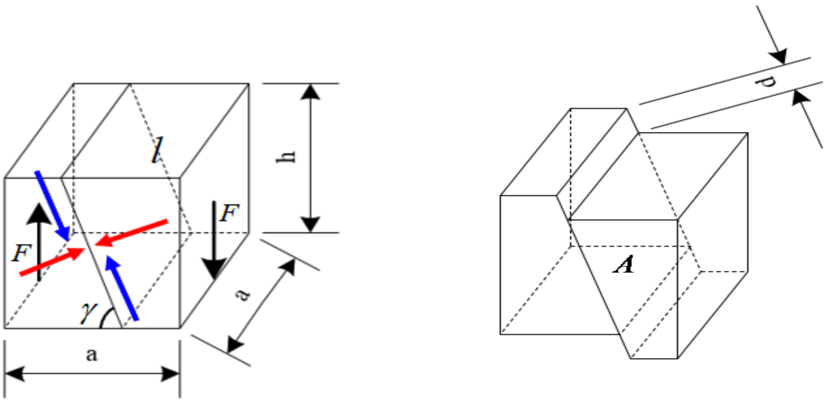
The calculation of the sliding displacement can be evaluated by Figure 3. As it shows, the length of the sliding surface is *l*, and once the shear strain of the element (ε) is calculated by the numerical simulation, the sliding displacement can be derived as follows:

$$d = \varepsilon \cdot l \tag{2}$$

Then the seismic moment magnitude can be obtained as follows:

$$M_w = \frac{2}{3}\lg M_0 - 6.06 \tag{3}$$

Once the evaluated seismic moment magnitude is larger than 2, then the hydraulic fracturing operation needs to be stopped (Skoumal et al., 2015).



(a) Shear sress applied on fault (b) Shear displacement of fault

Figure 3. Sketch map of the fault element sliding.

To provide recommendations for the hydraulic fracturing pressure, sensitivity analysis is conducted with considering the reservoir pore pressure increases. As shown in Table 1, three scenarios are conducted with increasing the pore pressure gradually. The purpose here is trying to understand the impact of field hydraulic fracturing process on the stress disturbance and even faults reactivation by using reservoir pore pressure increasing during water injection. Well J1 as shown in figure 1 is selected as the water injection well, and the normal distance between well J1 and the faults is 0.45 km.

Table 1. Multiple of pore pressure arising in hydraulic fracturing.

Hydraulic fracturing scenarios	Distance between injection well and the fault (km)	Times of pore pressure increase
1		$1.1p_0$
2	D=0.45	$1.2\,p_0$
3		$1.3\,p_0$

First, the multiple of pore pressure arising in hydraulic fracturing are set as 1.1, 1.2 and 1.3 times respectively. Then, based on the original pore pressure logging data, a series of new pore pressure logging data are assigned respectively, which are used to characterize different water injection pressure conditions. When the pore pressure at J1 well arises to 1.3 times, the shear strain produced by the fault units around the well is significantly higher than that of other elements in the fault.

Figure 4 shows the shear strain distribution of the fault, the rock elements near the injection well J1 have relatively larger shear strain. With the shear strain distribution, the sliding displacement can be further calculated according to equation (2). Figure 5 shows the number of failure fault elements and the seismic magnitude distribution of induced seismic activity moments. When the distance between the water injection well and the fault is 0.45km, when the water injection pore pressure of the fault in the study area rises 1.3 times, the number of damage units is the largest, and the moment magnitude of earthquake is about 1, the local stability of the fault is weakened, and the activation risk is increased; However, with the increasing distance between the water injection well and the fault, the fault in the study area is still basically in a stable state even if the reservoir is injected with water.

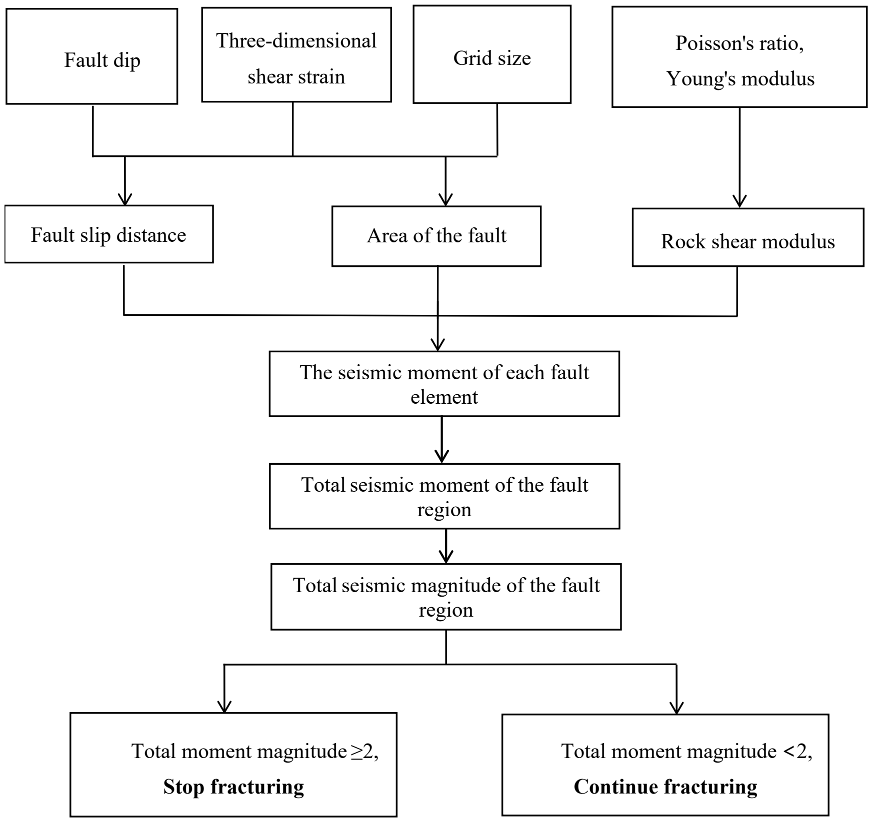


Figure 3. Evaluation flowchart of fault reactivation risk and the moment magnitude.

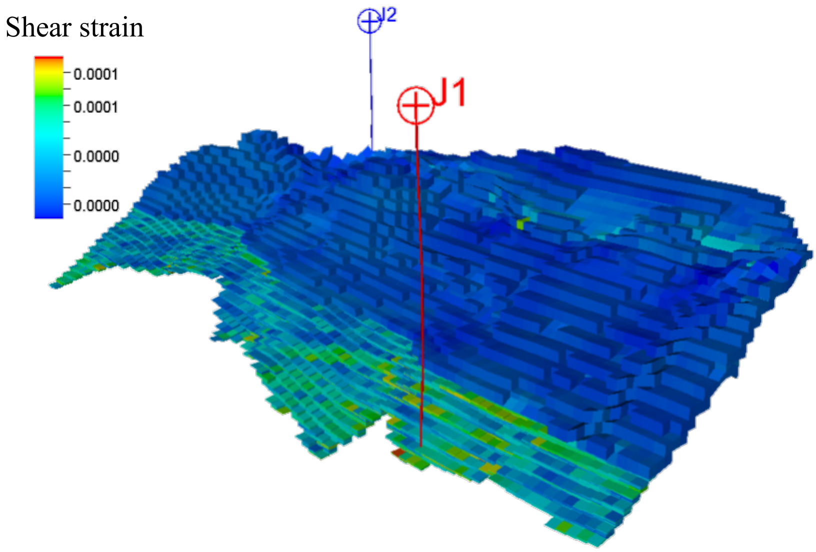
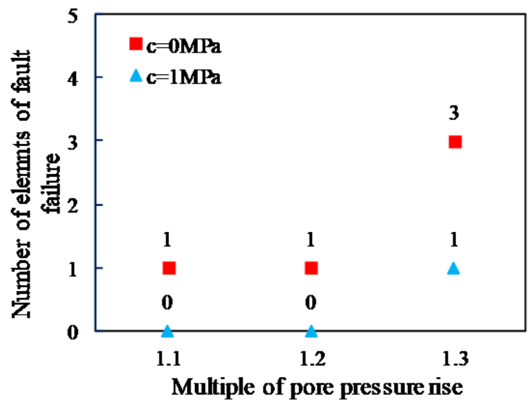
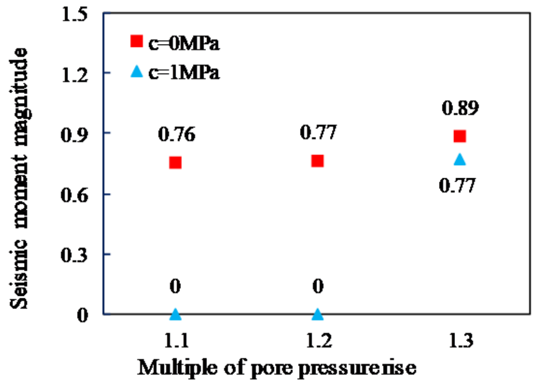


Figure 4. Shear strain distribution of the fault.



(a) Elements of fault failure



(b) Seismic moment magnitude

Figure 5. Mechanical response during water injection with D=0.45 km (Scenario 1 to Scenario 3).

CONCLUSION

In this work, a 3D geomechanics model with considering the actual stratum structure, non-uniform distribution of pore pressure and the natural faults is established. Based on the indoor experimental data at different depths of the wells, the mechanics reliability of the model is calibrated. Then the geo-stress distribution of the reservoir is calculated for each lithological formation. The stress regime of this reservoir is strike-slip under this evaluation. Finally, the stability of the faults in hydraulic fracturing is analyzed. Results show that the fault in the study area is partially damaged, and the local stress disturbing regions during water injection are limited. With the progress of the water injection, the pore pressure in the fault fracture-zone and fault core adjacent to the injection well increases obviously (increased about 1.1 times), resulting in a local instability of the fault. The induced seismic moment in fault regions is around 1 after water injection under simulated conditions, which means the fault will not produce large-scale instability.

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