Influence of heterogeneous fractured fault damage zones on shear failure onset during fluid injection

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Abstract. Fault stability analysis is traditionally performed by assimilating fault systems to surfaces. Yet, faults are complex and heterogeneous geological systems, whose compartmentalized architecture generally corresponds to an inner core (FC) of small thickness (i.e. principal fault plane) surrounded by outer, often fractured damage zones (DZ). Depending on the fractures' network characteristics, the latter compartment can be related to complex spatial distribution of hydro-poro-elastic properties, which can strongly influence the shear failure tendency of the fault zone during massive injection of fluid into reservoirs. Using the upscaled DZ properties derived from outcrop surveys at Cirques de Navacelles (South of France), we investigate this issue using coupled hydro-mechanical simulations in the framework of fully saturated orthotropic elastic porous media. By comparing the shear failure tendency for the heterogeneous DZ cases to the ones with homogeneous DZ, we highlight that: 1. Whatever the stress regime (extensional or compressional), the maximum injection pressure is greater in the heterogeneous cases; 2. Under extensional regime, the presence of the DZ limits the development of shear failure tendency in the center of the first DZ compartments directly adjacent to FC, whereas shear appears to rapidly develop along the whole reservoir thickness for the homogeneous case; 3. Under compressional regime, the presence of the DZ enhances the localization of shear failure along FC-DZ interface, whereas shear failure preferably develops in the injection zone in the homogeneous case.

Keywords: Fault stability, Fluid injection, Heterogeneous DZ.

1 Introduction

When fluid is injected into rock reservoir, changes in fluid pressure will affect stress state of rock mass; reduce fault strength leading to possible failure (e.g. shear reactivation of fracture). A central difficulty and the main challenge in evaluating the relationship between fluid pressure and fault slip lies in the variation in material properties across the fault zone. In the recent years, geomechanical analysis of fault zone behavior has been conducted for fault stability during fluid injection operations (see for instance for CO_2 storage applications [1,2]).

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Faults are complex and heterogeneous geological systems, which do not correspond to discrete surfaces as already postulated by many authors (e.g., [3,4]). A fault zone is generally composed of an inner core made of fine material, often impermeable, and where slip is concentrated called fault core (FC). It is surrounded by an outer damage zone (DZ) that often acts as a hydraulic pathway, because of the presence of a fracture network, whose characteristics (fractures' orientation, connectivity, lengths, density, etc.) depend on the distance to the core. The behavior of rock mass is therefore dependent on fracture networks' characteristics (spatial density, length, orientation, etc.), hence leading to heterogeneous hydro-mechanical DZ properties.

Some researches made the efforts to measure permeability and Young's modulus of fault zone [5]. Its results show that these properties are variable in DZ and strongly depend on their architecture. More recently, Nguyen et al. [6] has been estimated hydro-poro-mechanical properties by a numerical/analytical homogenization method. They brought out that the dependence of these properties in function of fracture density in DZ. A simple model by considering only reservoir part in fluid injection was used in [6]. The results revealed that the hydro-poro-mechanical influent to stability of FC. As a continuity of this recent work, a more realistic hydromechanical model is proposed in this paper to assess the shear tendency of reservoir during fluid injection. This is carried out by estimating the maximum sustainable overpressures that will not lead to failure. As shown by [7,8], the maximum overpressure strongly depends on the in-situ stress state, it means that compressional or extensional stress regime. Therefore, we propose to see how heterogeneous hydro-poro-mechanical properties influent shear tendency in reservoir during fluid injection.

In this context, the paper is organized as follows. Section 2 summarizes the homogenization process applied to fractured damage zone collected at Navacelles. Section 3 presents the numerical geological setting to model hydromechanical behavior of reservoir under influence of fluid injection. This model takes into account the usual homogeneous hydro-poro-mechanical properties of rock mass and also heterogeneous ones in different cases. Section 4 describes the numerical results with emphasis in the identification of critical zone. Some conclusions and remarks are given in section 5.

2 Homogenization method of fractured damage zone

Geological surveys were conducted at the Cirque de Navacelles, in the late Jurrassic platform carbonates of Languedoc, south of France. This site is located outside major fault systems and can be considered as a good analogue of the low-fractured rock formation targeted for CO_2 storage reservoir. The fault systems investigated can be assimilated to a layered system crossed by strike-slip fault zones characterized by fractured damage zones surrounding a fault core of small thickness. Based on the data collated on the fractures' characteristics of the DZ, a geostatistical model was defined in [6] to stochastically generate fracture networks representative of the onsite observations. A numerical homogenization strategy was then developed for determining the effective hydro-poro-mechanical properties of DZ. The results showed that the hydro-poro-mechanical homogenized quantities depend on the distance to fault core. Following these observations, empirical relationships were given linking the Young's modulus, permeability and Biot's coefficient with this distance (Fig. 1). The interested readers are invited to the work of [6] for more details about the procedure.

3 Model geometry and parameters

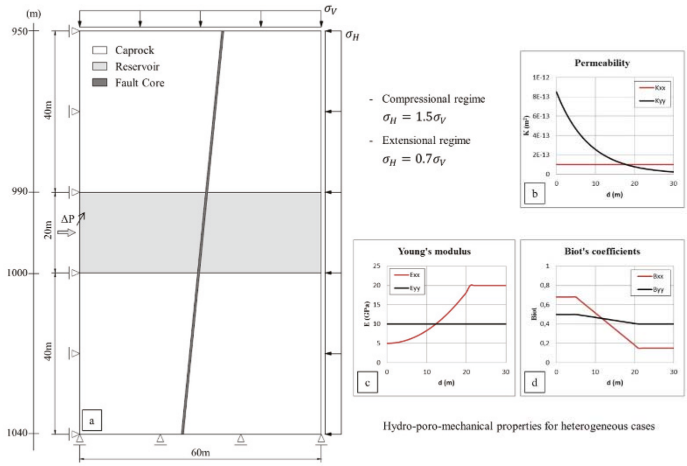

Fig. 1. a. Model geometry and boundary conditions; vertical (along x axis) and horizontal (along y axis) DZ properties as a function of the distance *d* to the fault core (located at *d=0*): b. Permeability; c. Young's modulus; d. Biot's cofficients.

A two-dimensional plain strain model (60m x 100m) was considered. Fig. 1 gives the geometry and initial conditions of boundary value problems. The reservoir 20m in thickness is assumed to be located at 1000m depth. It is bounded at top and bottom by low permeability 40m caprock (of 10^{-19} m^2). The domain is intersected by a fault core (FC) of 0.5m with a dip angle of 85° and very low permeability (of 10^{-17} m^2), surrounded by two DZ.

Fluid injection is modeled at left boundary of reservoir's level. An overpressure is increased from 0 to 25MPa (quasi-static loading). The maximum sustainable overpressure (ΔP_{max}) corresponds to the onset of rupture which occurs in the reservoir (shear slip in FC or in DZ). The problem was solved in the framework of fully saturated isothermal elastic porous media. Hydromechanical behavior of reservoir is assumed to be elastic orthotropic while the caprock behave as isotropic elastic materials. The whole domain is discretized by 5194 linear triangular-elements and numerical simulations are performed by using Code_Aster®.

In the present papers, two different tectonic stress regimes: compression ($\sigma_H = 1.5\sigma_V$) and extension ($\sigma_H = 0.7\sigma_V$) are studied. For each regime, we consider two different cases: homogeneous case (HO) and heterogeneous case (HE). The HO means that DZ's hydro-poro-mechanical properties are spatially constant while HE means that these parameters depend on the distance to FC. Related to the latter case (HE), hydro-poro-mechanical properties used are issued from data of in-situ campaign and then treated as described in Section 2. These properties in function of distance d to FC are described as follows, with K_{yy}, E_{xx}, B_{xx}, B_{yy} are vertical permeability, horizontal Young's modulus, horizontal and vertical Biot's coefficient of DZ, respectively:

$$K_{yy} = 8.10^{-2} e^{-0.12\,d} (m^{-2}) \tag{1}$$

$$E_{xx} = \begin{cases} 20 \text{ GPa } if\ d > 20\text{m} \\ 0.033\ d^2 + 5 \text{ (GPa)} if\ d \leq 20\text{m} \end{cases} \tag{2}$$

$$B_{xx} = \begin{cases} 0.15\ if\ d > 20\text{m} \\ 0.033\ d + 0.88\ if\ 5\text{m} \leq d \leq 20\text{m} \\ 0.68\ if\ d < 5\text{m} \end{cases} \tag{3}$$

$$B_{yy} = \begin{cases} 0.4\ if\ d > 20\text{m} \\ 0.007\ d + 0.37\ if\ 5\text{m} \leq d \leq 20\text{m} \\ 0.5\ if\ d < 5\text{m} \end{cases} \tag{4}$$

Other parameters K_{xx} (horizontal permeability), E_{yy} (vertical Young's modulus), B_{yy} (vertical Biot's coefficient), ν (Poisson's ratio), ϕ (porosity) are kept constant in these simulations. A bulk density of 2260kgm^{-3} is considered. The numerical parameters of rock formations are summarized in Table 1. The following notations are adopted: CHE for **He**terogeneous case in **C**ompressional stress regime; CHO for **Ho**mogeneous case in **C**ompressional stress regime; EHE for **He**terogeneous case in **E**xtensional stress regime; EHO for **Ho**mogeneous case in **E**xtensional stress regime.

Table 1. Properties of rock formations.

Case	E_{xx} (GPa)	E_{yy} (GPa)	K_{xx} (m^2)	K_{yy} (m^2)	B_{xx} -	B_{yy} -	ϕ (%)	ν -
Fault core	1	1	10^{-17}	10^{-17}	1.0	1.0	1	0.25
HE DZ	E_{xx}	10	10^{-13}	K_{yy}	B_{xx}	B_{yy}	15	0.25
HO DZ	20	10	10^{-13}	K_{yy}	1.0	1.0	15	0.25
Caprock	10	10	10^{-19}	10^{-19}	1.0	1.0	1	0.25

4 Numerical results

In this section, we focus on the hydromechanical behavior of reservoir. By increasing of overpressure ΔP at the left side of reservoir, pressure increases rapidly in left DZ and almost stops at FC. Pressure increase induces general reduction in effective stress that causes failure. The Mohr-Coulomb's criterion $\tau/\sigma'_n \leq \mu$ is used for evaluating the onset of rupture. By calculating $max(\tau/\sigma'_n)$, these results present the most unfavorable case at which the maximum sustainable overpressure can be obtained. For simplicity and conservative reason, the coefficient of friction $\mu = 0.6$ [2].

In these simulations, FC with low permeability plays a seal role. It limits the increasing of overpressure in the left part of reservoir. Biot's coefficients of FC are $B_{xx} = B_{yy} = 1.0$. For DZ, these coefficients are spatial dependent in heterogeneous case while are constant and equal 1.0 in homogeneous case. If Biot's coefficients are equal in both FC and DZ, the whole domain (FC and DZ) has the same initial effective stress. It is the case of CHO and EHO. In heterogeneous cases, DZ properties are spatial dependent. The nearby zone to FC has a smaller Biot's coefficient than in the far zone. Thus, the interface of DZ and FC is influenced by this property. Toward the DZ, Biot's coefficients are smaller, that's why initial effective stress in FC is more critical (dangerous) than in DZ.

For CHE case, first rupture is detected at two corners of left domain, in the interface between FC and DZ, corresponding to ΔP = 15MPa (Fig. 2.a). After this first observation, rupture continues to develop from two corners to DZ. From ΔP = 20MPa a failure's zone is also observed in the middle of FC, developed from interface DZ/FC to FC (Fig. 2.c). Meanwhile in CHO, first failure is detected from upper corner at ΔP = 8.5MPa but a strong development of failure is then observed at left boundary (injection zone) (Fig. 2.b,d). It developed from this injection zone to FC and all the left domain is activated after 13MPa of overpressure.

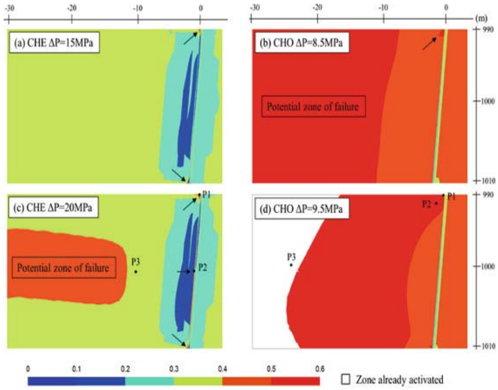

Fig. 2 $max(\tau/\sigma'_n)$ for compressional cases. Arrows indicate shear initiation.

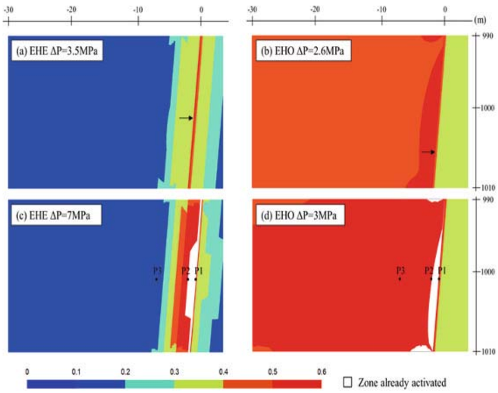

Fig. 3. $max(\tau/\sigma'_n)$ for extensional cases. Arrows indicate shear initiation.

Failure appears very soon in extensional case, after about 3.5MPa in EHE and 2.6MPa in EHO (Fig. 3.a,b). In EHE case, it begins from the middle of FC and then in

DZ after activates almost the whole FC. In EHO case, failure develops both in FC and DZ. As influenced by heterogeneous hydro-poro-mechanical properties, failure development is quite different from EHE to EHO. The first shear activation for EHE and EHO is detected at the same overpressure but after that, at each level of ΔP, the activated zone in EHO is wider than in EHE. Furthermore, while failure zone in EHE appear from the middle to upper and lower boundary, but in EHO it does appear at the same time from the middle and two small zones in top and bottom of reservoir. This is directly related to the influence of caprock.

5 Conclusion

Numerical investigation has been presented in this paper to investigate the influence of heterogeneous fractured fault damage zones on shear failure onset during fluid injection into porous reservoir. Rock reservoir's behavior has been treated as an orthotropic material with heterogeneous hydro-poro-mechanical properties issued from the recent works of [6]. Different stress regimes such as compressional and extensional case have been simulated. The results confirm that increasing of overpressure reduce effective stresses and thus promote failure. Shear activation tendency has been analyzed. The results reveal the most dangerous situation by evaluating the maximum of fraction $max(\tau/\sigma'_n)$ which induce rupture according to Mohr Coulomb criterion.

Along the papers, heterogeneous cases are well distinguished with homogeneous ones. The results show clearly the consequence of using hydro-poro-mechanical properties which describes heterogeneous fracture network. This demonstrates the fact that due to heterogeneous properties, the maximum sustainable overpressure causes failure could be increased. The results help to improve the understanding of different manners and locations of failure while using "real" properties in numerical modeling.

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