Poro-mechanical properties evolution under hydrostatic stress after induced damage

Cong HU[a], Frédéric SKOCZYLAS[b]

a. Centrale Lille, CS20048, F-59651 Villeneuve d'Ascq Cedex, France, cong.hu@ec-lille.fr
b. Centrale Lille, CS20048, F-59651 Villeneuve d'Ascq Cedex, France, frederic.skoczylas@ec-lille.fr

Résumé :

Pour le réservoir souterrain de stockage de gaz, l'état de contrainte peut être modifié par l'injection et épuisement du gaz naturel. Le changement d'état de contrainte peut avoir une influence significative sur les propriétés poro-mécaniques des roches réservoir. Dans cette recherche, l'évolution des propriétés poro-mécaniques sous contrainte hydrostatique après dommages induits est étudiée. A pression de confinement constante, la contrainte déviatorique est maintenue à une valeur constante (inférieure à la valeur de contrainte maximale) puis déchargée à zéro. En raison des dommages, le matériau est considéré comme étant isotrope transverse. Le coefficient de Biot en direction axiale et en direction latérale est mesuré lorsque la contrainte déviatorique est déchargée à zéro. Cette procédure est répétée plusieurs fois avec le chargement / déchargement cyclique de la contrainte déviatorique (la valeur de la contrainte déviatorique augmente progressivement). En général, on constate que le coefficient de Biot dans la direction latérale est plus grand que celui dans la direction axiale. Il est compatible avec l'évolution des propriétés anisotropes. La raison en est que les micro-fissures induites sont principalement orientées dans la direction axiale. Dans la direction latérale, de plus en plus de micro-fissures seront comprimées.

Abstract :

For underground gas storage reservoir the stress state may be changed by cyclic injection and depletion of natural gas. The change of stress state may have a significant influence on the poro-mechanical properties of reservoir rocks. In this research the poro-mechanical properties evolution under hydrostatic stress after induced damage is investigated. At constant confining pressure deviatoric stress is maintained at a constant value (smaller than the peak stress value) and then unloaded to zero. Because of damage the material is thought to be transversely isotropic. Biot's coefficient in axial direction and lateral direction is measured when deviatoric stress is unloaded to zero. This procedure is repeated several times with cyclic loading-unloading of deviatoric stress (the value of deviatoric stress increased gradually). Generally, it is found that the Biot's coefficient in lateral direction is larger than that in axial direction. It is consistent with the evolution of anisotropic properties. The reason is that the induced micro-cracks are mainly oriented in the axial direction. In lateral direction more and more micro-cracks will be compressed.

Mots clefs: poro-mechanical properties; deviatoric stress; induced damage

1 Introduction

Underground gas storage plays a vital role in competitive natural-gas markets and is a beneficial economic method to compensate the imbalance between supply and demand [1-3]. When market demand falls below the supply the natural gas is injected into storage facilities and it is withdrawn from the storage environment to supplement the supply from the pipeline when the demand exceeds the supply [4, 5]. There were 688 natural gas storage facilities operated in the world as of January 2013 and depleted gas reservoir is by far one of the most popular methods for gas storage because they are usually available in close vicinity of pipelines and include some wells and usable facilities to reduce the costs[2, 6].
During injection or extraction natural gas into or from underground formation understanding hydraulic and mechanical interaction is of vital importance [7, 8]. Biot's coefficient is one of the most important parameter for coupling between mechanical variables, stress and strain, and the pore pressure [9, 10].
The stress states or stress history have a big influence on the poro-mechanical properties of rocks. In this research a series of triaxial test was made at different confining pressures to investigate the poro-mechanical properties after induced damage.

2 Test material and apparatus

The sandstone is obtained from a field of a depleted gas reservoir in east of France. The initial porosity of the sandstone measured with distilled water is about 19.4%. The height of the cylindrical sample used in our tests is 69.5±0.2mm and the diameter is 37.5±0.2mm. Figure 1 is the micro optical and computed tomography (CT) scanning images. From the micro optical image we can find that there are very small particles between two big particles. The grain size is mainly located between 250 and 300μm. The resolution of CT scanning is 30μm. The size of the sample for CT scanning is 69.5mm in height and 37.5mm in diameter. Several horizontal sedimentary bands can be seen from the CT scanning image.

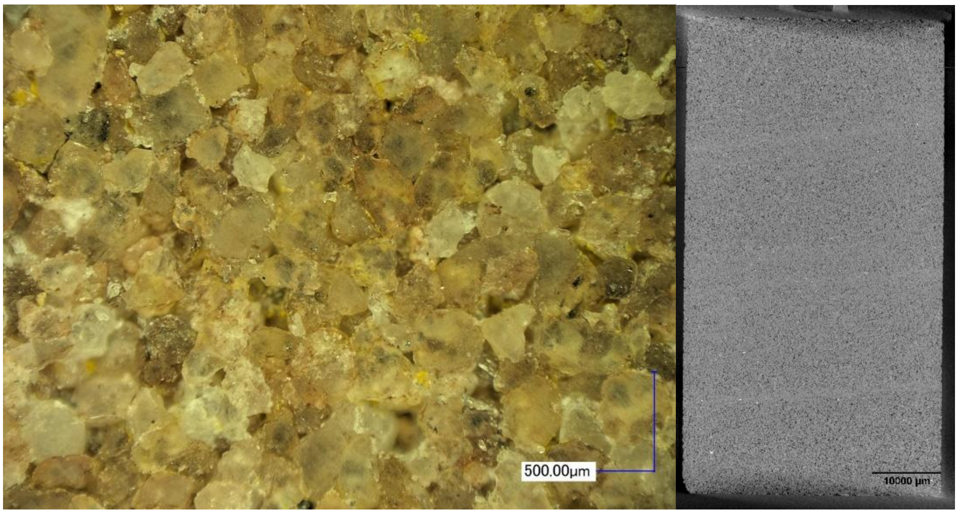

Figure 1 micro optical and computed tomography scanning images

Figure 2 is the schematic illustration of the autonomous, self-compensated triaxial compression apparatus. The coordinate is also shown in the figure. x_1 is the axial direction. During test the sample is sealed by a rubber membrane. Two cross gauges were glued at the opposite side of the sample. Each gauge can measure two strain values, in axial and lateral directions respectively. The strain values are recorded by a Labview system (National Instruments). Compression is positive and tension is negative. The final axial (ε_a) and lateral (ε_l) strains are the average of the two gauges. Volumetric strain equals to $2\varepsilon_l+\varepsilon_a$. Deviatoric stress ($\sigma_1$-$\sigma_3$) is applied by a press machine. The loading speed is 0.12mm/min. The fluid used to apply the pore pressure (p_i) is pure argon. After each loading step of pore pressure about 10mins were waited for strain stability.

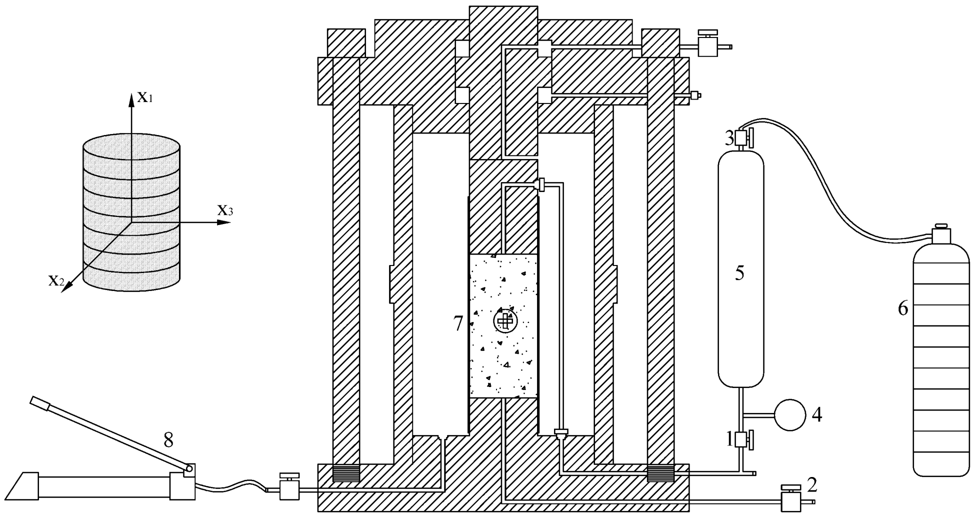

Figure 2 Schematic illustration of the triaxial compression apparatus (1-3 valves, 4 manometer, 5 accumulator, 6 gas reservoir, 7 sandstone sample, 8 pump)

3 Test Results

The initial state of the sandstone is thought to be isotropic. When deviatoric stress is loaded to a constant value and then unloaded to zero there will exist some irreversible pores and micro-cracks especially distributing in the axial direction. Therefore the current state of the sample is more close to transverse isotropy.

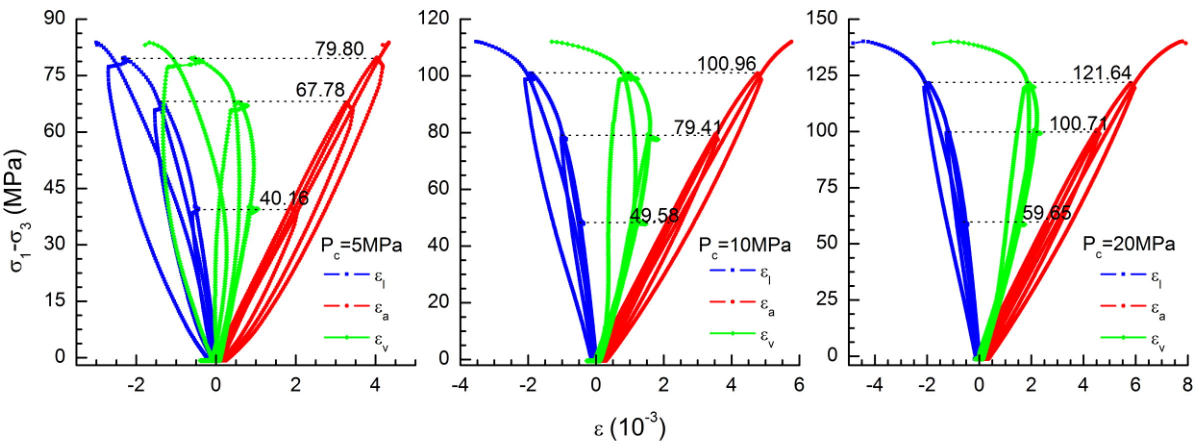

Figure 3 Stress-strain curves under different confining pressures

The poro-mechanical properties evolution under three different confining pressures (5, 10, 20MPa) with damaged conditions were evaluated in this section. The stress-strain curves at different confining pressures were shown in Figure 3. The maximum deviatoric stress at different cycles was also marked on the figure. Different level of deviatoric stress represented different damaged level. After deviatoric stress was unloaded to zero the following two test procedures were made: (1) decrease confining pressure with a step of 1MPa, (2) after that confining pressure was loaded to the initial value and then increase pore pressure with a step of 1MPa. It should be noticed that the variation of pore pressure was the same with the variation of confining pressure at each step. At all the three different confining pressures three loading-unloading cycles were made. In this research the following relationship was first used to evaluate the induced anisotropic properties.

$$\beta_i = \frac{\Delta\varepsilon_i^g}{\Delta\varepsilon_i^c} \quad i = (1,3) \tag{1}$$

Where $\Delta\varepsilon_i^g$ represents the variation of strain induced by pore pressure and $\Delta\varepsilon_i^c$ represents the variation of strain induced by confining pressure. i=1 represents the axial direction and i=3 represents the transverse isotropic plane in lateral direction.

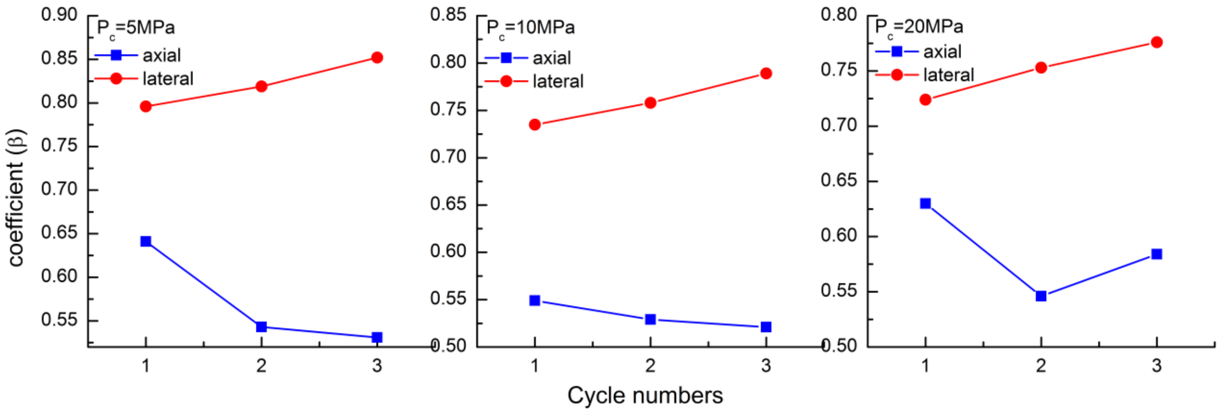

Figure 4 induced anisotropic properties evolution with cycle numbers

The results are shown in Figure 4. We found that the coefficient in axial direction was always smaller than that in lateral direction which indicated that the material became transversely anisotropic. Generally, with the increase of cycle numbers or damage level we found that the coefficient in axial direction decreased and the value in lateral direction increased. This phenomenon indicated that the degree of damage grew gradually with cycle numbers and increase of deviaoric stress. In axial direction more microcracks existed and in lateral direction more microcracks were compressed.

The components of anisotropic biot's coefficients in two different directions can be given as follows [11]:

$$b_1 = \frac{1/\Delta\varepsilon_1^c}{1/\Delta\varepsilon_1^c + v_1/\Delta\varepsilon_3^c} \cdot \left(2v_1 \frac{\Delta\varepsilon_3^g}{\Delta\varepsilon_3^c} + v_1 \frac{\Delta\varepsilon_1^g}{\Delta\varepsilon_3^c} + (1-2v_1)\frac{\Delta\varepsilon_1^g}{\Delta\varepsilon_1^c} \right) \tag{2}$$

$$b_2 = b_3 = \frac{1/\Delta\varepsilon_1^c}{1/\Delta\varepsilon_1^c + v_1/\Delta\varepsilon_3^c} \cdot \frac{\Delta\varepsilon_3^g + v_1\Delta\varepsilon_1^c}{\Delta\varepsilon_3^c} \tag{3}$$

Where b_1 is the Biot's coefficient in axial direction and b_3 is the Biot's coefficient in lateral direction. v_1 is a poisson's ratio which can be easily defined by the linear loading stage at each loading cycle.

The evolution of biot's coefficient is shown in table 1. The evolution of the coefficient is consistent with the anisotropic properties. The coefficient in lateral direction is always larger than that in axial direction. The reason is that the induced irreversible microcracks mostly oriented in axial direction and the number of microcracks in lateral direction reduced most [12, 13]. Moreover Poisson's ratio is gradually increased with increase of damage level.

Table 1 Evolution of the biot's coefficient under different confining pressures

P_c (MPa)		5	10	20
1st cycle	b_1	0.710	0.616	0.663
	b_3	0.756	0.698	0.707
	ν_1	0.299	0.221	0.216
2nd cycle	b_1	0.659	0.610	0.610
	b_3	0.738	0.710	0.701
	ν_1	0.298	0.222	0.215
3rd cycle	b_1	0.697	0.621	0.656
	b_3	0.744	0.731	0.733
	ν_1	0.388	0.239	0.232

4 Conclusions

The poromechanical properties of a sandstone at different confining pressures after induced damage are investigated. The initial state of the material is assumed to be nearly isotropic. After the cyclic loading of deviatoric stress the material will become anisotropic or transversely isotropic. The anisotropic properties can be evaluated by the ratio between strain caused by pore pressure and that caused by confining pressure. The ratio in lateral direction is larger than that in axial direction. The evolution of anisotropic Biot's coefficient is in agreement with the anisotropic properties. Biot's coefficient in lateral direction is also larger than that in axial direction. The poisson's ratio also increases gradually with increase of damage level. The reason is that the induced micro-cracks are mainly oriented in the axial direction. In lateral direction more and more micro-cracks will be compressed.

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