International Journal of Research in Engineering, Science and Management
Volume 7, Issue 1, January 2024
https://www.ijresm.com | ISSN (Online): 2581-5792

Rock Mechanics Applications in Petroleum and Natural Gas Engineering

Michael Arvanitis*
Casa College, Nicosia, Cyprus

***Abstract*: This paper is an overview of major applications of rock mechanics in petroleum and natural gas engineering and gives the background and theory behind the basic elements of the methods applied.**

***Keywords*: natural gas, petrophysics, oil and gas, geophysics, petroleum.**

1. Introduction

Rock mechanics is the science dealing with the theoretical and applied behavior of rock due to either external natural or man-made stresses. Rock mechanics are widely used by civil as well as mining engineers a long time ago. Recently rock mechanics has been applied to solve problems in many aspects of petroleum engineering such as drilling, reservoir, and production engineering. In the following sections, light will be shed on the involvement of rock mechanics in solving the many problems that may encountered during the various petroleum engineering activities such as drilling, reservoir, and production engineering (Fig. 1).

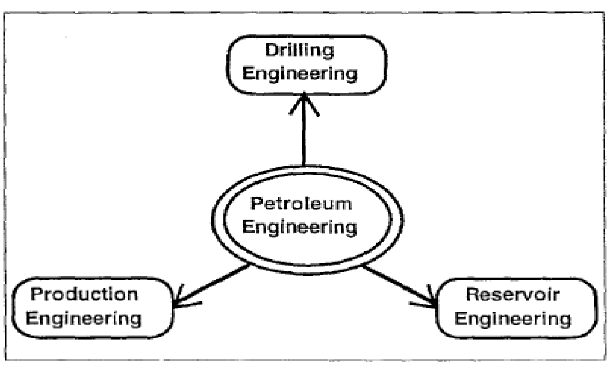

Fig. 1. Main branches of petroleum engineering science [2]

2. Assessment of Rock Mechanical Properties

Various rock properties are required as input in any attempt to solve various engineering problems. Rock mechanical testing of cores must be designed according to the purpose of the investigation. If the objective is to predict borehole instability, then the testing procedures may not be the same as in reservoir compaction.

These outlined testing procedures were set to minimize human errors. Rock mechanical data are obtained either by testing representative rock samples in the laboratory or by analyzing field records. Triaxial testing of rock samples provides important data such as failure criteria, frictional properties apparent cohesion and angle of internal friction), and arid elastic properties (Young's modulus, bulk modulus, Poisson's ratio, etc.). Many other properties can be measured based on rock testing such as pore and bulk compressibility, permeability stress sensitivity, crushing resistance, P & S velocities, swelling, etc. [1].

Details of these tests can be found in any professional rock mechanics Field data may provide us with formation lithology, continuous record of formation porosity (as an indication of the rock strength), formation fluids analysis, reservoir geology, etc. (Table 2). Well logs provide continuous data versus depth but do not directly measure the parameters that are needed for a rock mechanical analysis. Rock mechanics have been used to investigate and solve several problems in the oil industry. Table (3) summarizes these problem management techniques and the data required.

3. Applications in Drilling Engineering

Several problems occur repeatedly during oil and gas well drilling. Normally, the first attempt to solve such problems is based on experience. If all methods fail to solve such problems, a rock mechanics study is the last at this stage, rock mechanics analysis will be difficult due to the lack of data, and rock samples, therefore, back analysis only solution. Thus, rock mechanics principles must be considered from the beginning, and rock and reservoir mechanical bases must be established to speed up solving any new problems. On average, drilling problems due to borehole instability are responsible for about 10 to 20 the drilling cost of a well. 80 to 90 % of these instabilities occur when drilling through shale sections. These instabilities cost the industry around $40-500 million per year Problems generally build up with time, starting with the fragmentation of the borehole wall, followed by transfer of the fragmentation to the annulus and finally creating problems such as sticky hole, hole fill, stuck pipe, lost circulation, etc. A Borehole can be kept open and stable if special care is given to ensure good mud sealing capability (i.e. mud cake efficiency).

Controlling the drilling mud water activity is crucial to stop shale swelling. Water activity is the property that controls the

*Corresponding author: m.arvanitis@casacollege.ac.cy

Table 1
Wellbore and reservoir problems related to rock mechanics

Stage	Problems	Data possibly required to solve encountered problems
Exploration	Petroleum migration, Traps, Reserve estimation, etc.	- Failure criteria. - Rock-fluid compatibility. - Rock elastic properties. - In-situ stress state. - Well orientation and inclination. - Drilling fluid properties. - Swelling tendency. - Mud cake efficiency. - P & S velocities.
Drilling	Borehole instability, Loss of circulation, Casing collapse, Bit balling, etc.	
Production	Sand production, Perforation stability, Hydraulic fracturing, Propant crushing, etc.	
Reservoir	Permeability-stress sensitivity, Rock-fluid interaction, Subsidence, Fracture identification, etc.	

magnitude and direction of the filtrate invasion. The water activity of a 100 % water-saturated rock equals unity. Therefore, the water activity of the drilling fluid must be always kept lower than that of the formation being drilled. Water invasion into shale formations causes them to swell and lose a large portion of their strength and therefore fail into the borehole and lead to borehole instability. In sandstone formations, water invasion leads to pore pressure build-up [2].

The build-rip in the formation pore pressure will change the magnitude of the effective in-situ principal stresses responsible for formation stability. Upon change in the effective in-situ stresses, shear failure could be the result which can shift the borehole laterally causing a tight hole, and abnormal torque and overpull. Drilling fluid weight provides a radial support to the sides of the borehole. The magnitude of the radial support is highly dependent on the mud cake efficiency. Therefore, the radial support provided by the drilling mud is not effective if the mud cake efficiency (quality) is very low. A high mud cake quality allows no filtration.

Table 2
Type of rock mechanical tests

Uniaxial tensile and compressive strength.
Triaxial compressive strength and failure criteria.
Cement-casing and Cement-formation bond strength.
Direct and indirect shear strength.
Permeability stress sensitivity.
Elastic and Frictional properties.
Matrix and pore compressibility.
P & S velocities.
Propant crushing resistance.
Swelling and wet/dry rock strength.

The Magnitude of the mud weight required to keep a borehole open can be predicted using rock mechanics principles]. Borehole orientation concerning the maximum horizontal in situ principal stress is very important from the point of view of borehole instability analysis. For example, horizontal boreholes drilled parallel to the minimum horizontal in-situ principal stress are the most stable among those drilled using other horizontal orientations. Therefore, rock mechanics must be used to assess the risks associated with vertical, high-angle, and horizontal oil and gas wells drilling [2].

4. Applications in Production Engineering

When producing reservoir fluids over a long period, the tile reservoir will be depleted, and compaction and subsidence may be the result. Subsidence of the productive formation and the overlying strata could mobilize (activate) stable faults or shear surfaces. Hence, an expensive oil well could be lost. Formation subsidence may damage cement sheath around cased wells and create micro annuli which allow abnormal pressured fluids either to damage or to corrode the casting string.

Another rock mechanics-related problem may be encountered during hydrocarbon production called sand production. Sand production is the production of small or huge amounts of solids along with the reservoir fluids down to the borehole and along to the surface. Sand grains forming the productive formation will be produced along with the reservoir fluids if excessive production (drawdown) is implemented.

Excessive drawdown may lead to the failure of stabilized sand arches formed around the production perforations in the case of unconsolidated sandstone formations or to the generation of localized shear failures near the wellbore in the productive formation in the case of consolidated sandstones. The produced sand comes either from the failed sand arches or the induced shear surfaces. Numerous problems could be raised due to sand production such as wear of downhole and surface production equipment, casting wear and collapse, unnecessary cost that comes from dumping dirty sands, etc. Several rock mechanical solutions have been developed by many researchers and have been dramatically minimized the problem of sand production When designing hydraulic fracturing, the propant to be used to keep the induced fracture open, must be tested. Upon relieving the injection pressure fracturing which is applied on the fracturing fluid, the fracture will close, and the proppant will be stressed. Therefore, the proppant crushing resistance must be examined to keep the induced fracture open and not to close the generated flow paths by the debris of the crushed proppant.

The height end orientation of the hydraulically induced fractures is a function of the in-situ stress state. Therefore, rock mechanics must be implemented in designing hydraulic fracturing to avoid gas migration and water coming [2].

5. Applications in Reservoir Engineering

The accuracy of reservoir reserve calculations is highly dependent on the measured reservoir rock compressibility Rock compressibility is a function of the in-situ stress state and it can be accurately measured at the rock mechanics laboratories. Upon pressure drop in the oil gas reservoir, secondary and tertiary recovery methods are applied to increase hydrocarbon recovery When water flooding or thermal recovery techniques are applied, thermal stresses may be generated to the difference in temperature between the reservoir environment and the injected water.

Table 3
Implementation of rock mechanics in solving petroleum engineering problems

Phase	Problem	Potential solutions	Data required
Drilling Engineering	Borehole instability	changing mud weight. selecting mud type. controlling mud cake efficiency. managing well orientation.	rock elastic properties. rock failure criteria. in-situ stress stale. rock swelling characteristics. well orientation. well inclination. dulling fluid properties. mud cake efficiency.
Production Engineering	Sand production Perforation stability Fracturing height and orientation Water injection	selecting perforation location selecting completion type. controlling fluid drawdown. controlling production rate. managing propant crushing resistance selecting propant type. selecting fracturing fluid type. measuring rock compressibility. controlling injection rate. controlling water temperature. testing water-rock compatibility. controlling injection rate.	rock elastic properties. rock failure criteria. in-situ stress state. rock swelling characteristics. well orientation well inclination. reservoir description.
Reservoir Engineering	Reserve Calculation Compaction Subsidence Reservoir stress sensitivity	selecting well location. controlling production rate controlling injection rate.	rock elastic properties. rock failure criteria. in-situ stress state. rook swelling characteristics. well orientation. well inclination. reservoir description. permeability sensitivity to stress.

These induced thermal stresses are responsible for activating faults and induced shear surfaces. is injected either to maintain the reservoir pressure or to displace the residual oil, if the injected water is incompatible, the cementing material bonding formation grains together may be damaged, and the result could be formation damage, sand production, or borehole stability in low permeability reservoirs, water injection may increase the capillary forces and lead to pore collapse (i.e. mechanical permeability damage). When drilling adjacent wells from a single platform, borehole stability will be critical. The ignorance of rock mechanics when investigating the above reservoir problems may cause several problems at different occasions during the reservoir life, thus decreasing the reservoir productivity and profits [2].

6. Measurement of Rock Mechanical Properties

A. Introduction

Mohr-Coulomb failure criterion was introduced to rock mechanics by Jaeger in the year 1959 G. by combining the work of Mohr and Coulomb. This criterion states that shear failure across a plane is restricted by the cohesion of the material. This criterion can be expressed mathematically as follows [3]:

$$\tau_f = \tau_o + \sigma \tan \varphi \tag{1}$$

Where:
τ_f and σ = Shear and normal stresses respectively,
τ_O = Apparent or inherent cohesion, and
φ = Angle of internal friction.

The evaluation of the Mohr-Coulomb failure criteria needs to carry out many triaxial tests on rock samples at various confining pressures. From these data a series of Mohr's circles can be plotted as shown in Fig. 2. Then the locus of the tangent points of circles is drawn, developing the failure envelope for the tested rock which defines the boundary between stable and unstable stress states. Once the failure criterion is established, the failure state (instability) at any other conditions can be predicted.

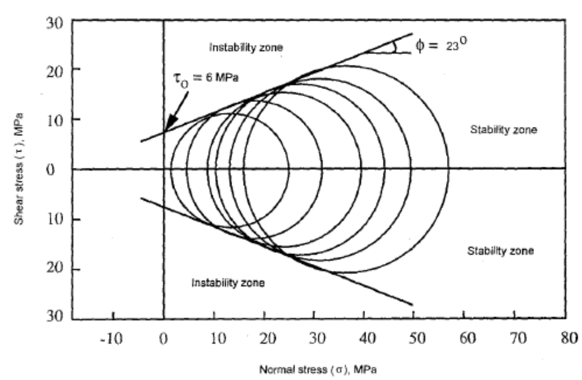

Fig. 2. Mohr-Coulomb failure criterion for natural intact shale [1]

Poisson's ratio is another important rock property which is defined as the ratio of the lateral strain to the axial strain in an axially stressed sample. If the axial and lateral strains are measured during triaxial testing to determine the Mohr-Coulomb failure criterion, Poisson's ratio ν can be calculated as well. Alternatively, Poisson's ratio can also be estimated using the following relationship [4]:

$$\varphi = Sin^{-1}\left[\frac{1-\nu}{1+\nu}\right] \tag{2}$$

Equation 2 provides only estimated values of Poisson's ratio.

However, for more accurate values of Poisson's ratio, data obtained using the triaxial tests must be used. The uniaxial (unconfined) compressive strength (σ_c), apparent cohesion and angle of internal friction are combined as shown in the following equation [3]:

$$\sigma_c = \tau_o \frac{2Cos\varphi}{1-Sin\varphi} \quad (3)$$

The objective of this study is to find a simple correlation between the uniaxial compressive strength and the apparent cohesion of rocks. Using this correlation, several important mechanical parameters can be estimated including, the angle of internal friction, Poisson's ratio, and Mohr-Coulomb failure criterion.

7. Measurement of Unconfined Compressive Strength

Unconfined compressive strength can be evaluated directly by performing laboratory testing on a cylindrical core sample. A gradual axial stress is implemented on the core sample up to failure. The peak value of the axial stress is taken as the unconfined compressive strength of the sample as shown in Fig 3. When adequate samples are available, repeat testing may be conducted to determine the average unconfined compressive strength value. If no adequate core samples are available, the unconfined compressive strength can be determined indirectly from the triaxial testing data using Equation 3.

The knowledge of the unconfined compressive strength of a formation is advantageous in providing important data points to determine a failure locus (i.e. Mohr failure envelope), in defining parameters needed in constitutive modeling, and in indicating wellbore instability.

8. Measurement of Triaxial Compressive Strength

Triaxial compressive strength can be evaluated by performing laboratory testing on cylindrical core samples. Gradual axial stress is implemented on the core sample at a constant confining pressure generated using a servo-controlled pump to failure. The peak value of the axial stress is taken as the confined compressive strength of the sample at the specified confining pressure. When adequate samples are available, repeated testing is conducted to determine the failure locus (envelope). Confined compressive strength can be estimated using a multi-state triaxial compressive test conducted on a single core sample if there is lack in core samples. If triaxial testing is performed at several confining pressures, and preferably if unconfined compressive and tensile test data are available, a representative failure locus can be constructed. The selected confining pressures for triaxial testing are generally spread over a range from very low to beyond the maximum anticipated in-situ effective stress conditions. Measurements can be performed at in-situ temperature and pore pressure can be applied as well.

The knowledge of the confined compressive strength of a formation is advantageous in providing an important data point to determine a failure locus (i.e. Mohr envelope), in defining parameters needed in constitutive modeling, in indicating wellbore instability, and in providing information for hydraulic fracturing design.

9. Measurement of Apparent Cohesion

Apparent cohesion is a measure of grain-to-grain bonding strength. For example, sand has no apparent cohesion. The value of the apparent cohesion can be obtained from the intersection of the failure envelope with the shear strength axis (y-axis) in the Mohr-Coulomb criterion.

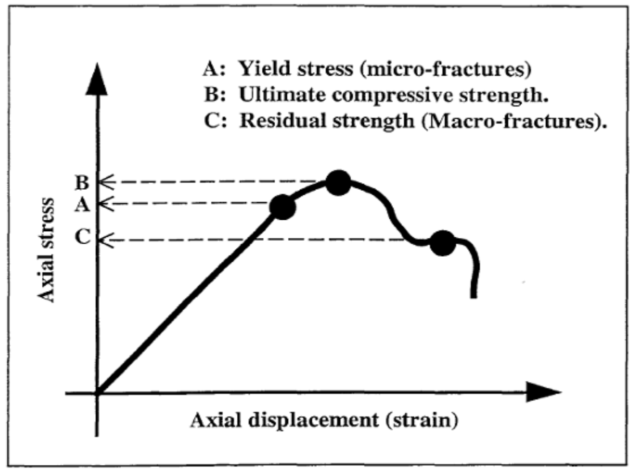

Fig. 3. Stress versus deformation in a compression test [5]

10. Measurement of Angle of Internal Friction

Internal friction is the resistance of movement between rock particles (grains). The value of the angle of internal friction is the cotangent of the slope of the failure envelope (the tangent line to Molar circles). When triaxial testing facilities are not available the angle of internal friction can be determined using equation 2 [4].

However, the angle of internal friction measured using this method is lower than that determined from triaxial loading. The triaxial strength test gives friction angles at failure with shear strength fully mobilized along the failure plane, while the strain measurement in the uniaxial compressive loading method only gives the intact rock friction angles.

11. Measurement of Poisson's Ratio and Young's Modulus

The two main elastic constants that are usually used in most rock failure models are Poisson's ratio and Young's modulus. Young's modulus is the measure of the stiffness of the rock material, i.e. the sample resistance against the compressive stress (load). Poisson's ratio is a measure of the simultaneous change in elongation and in the cross-sectional area within the elastic range during a tensile or compressive test. Elastic constants are evaluated from the stress versus lateral and axial strains measured in conjunction with the triaxial compressive testing. Elastic constants can be estimated from using the following equations [5]:

$$E = \left[\frac{\sigma_{z1}-\sigma_{z2}}{\xi_{z1}-\xi_{z2}}\right] \quad (4)$$

$$\nu = \left[\frac{\xi_{x1} - \xi_{x2}}{\xi_{z1} - \xi_{z2}}\right] \quad (5)$$

Where:

E = Young's modulus
ν = Poisson's ratio
σ_{z1} = Stress at axial point z1
σ_{z2} = Stress at axial point z2
ξ_{z1} = Strain at axial point z1
ξ_{z2} = Strain at axial point z2
ξ_{x1} = Strain at lateral point z1
ξ_{x2} = Strain at lateral point z2

The parameters shown are measured in the laboratory using strain gauges attached to the test sample during the unconfined compressive strength.

12. Conclusion

This paper presented an overview of major applications of rock mechanics in petroleum and natural gas engineering.

References

[1] Musaed N. J. Al-Awad: "Simple Correlation to Evaluate Mohr-Coulomb Failure Criterion Using Uniaxial Compressive Strength.", Journal of King Saud University, Engineering Sciences, vol. 14, no. 1, pp. 137-145, 2001.
[2] Musaed N. J. Al-Awad: "Rock Mechanics Applications in Petroleum Engineering Practices.", Oil and Gas European Magazine (International Edition of Erdoil Erdgas Kohil), Germany, vol. 4, no.1, pp. 18-20, December 1998.
[3] Erling F. et. al.: "Petroleum related rock mechanics.", Elsevier publishing company, 1992.
[4] Turk, N. and Dearman, W. R.: "Estimation of friction properties of rocks from deformation measurements.", 27th US symposium on rock mechanics, June 23-25, 1986.
[5] Musaed N.J. Al-Awad and Talal Y. AlAhaidib: "Estimating the Amount of free Sand in the Yielded Zone around Vertical and Horizontal Oil Wells.", SPE-SA0526, the 2005 SPE Technical Symposium of Saudi Arabia Section held in Dhahran, Saudi Arabia, 14-16 May 2005.
[6] Palmstrom A.: "A rock mass characterization system for rock engineering purposes.", Ph.D. thesis, Oslo University, Norway, 1995.
[7] Monitoring Degree of Metamorphism in a Four-stage Alteration Process Passing from Pure Limestone to Pure Marble by Costas I. Sachpazis Associate Professor, Department of Geotechnology and Environmental Engineering, Technological Educational Institute of West Macedonia, Koila 50100, Kozani, Greece, The Electronic Journal of Geotechnical Engineering-Volume 9, 2004 — Bundle B.
[8] Luiza Aline Fernandes: "The influence of mineralogy, chemistry and physical engineering properties on shear strength parameters of the Goat hill rock pile material, Questa molybdenum mine, New Mexico.", M. Sc. Thesis, New Mexico Institute of Mining and Technology, Department of Mineral Engineering, Socorro, New Mexico, March, 2006.
[9] Jonny Sjoberg: "Estimating rock mass strength using the Hoek-Brown failure criterion and rock mass classification.", Internal Report no. BM 1997:02, Department of Mining Engineering, Division of Rock Mechanics, Lulea University, Sweden, August 1997.
[10] D. Li.G. Chen, G.A. Chukwu, S. L Patill and S. Khataniar: "Laboratory evaluation of chemical grouts for wellbore stabilization.".
[11] Hae-sik Jeong, Seong-seung Kang, Yuzo Obara: "Influence of surrounding environments and strain rates on the strength of rocks subjected to uniaxial compression.", International Journal of Rock Mechanics & Mining Sciences 44 (2007) 321–331.
[12] Liang, C. Yang, Y. Zhao, M.B. Dusseault, J. Liu: "Experimental investigation of mechanical properties of bedded salt rock.", International Journal of Rock Mechanics & Mining Sciences, 44(2007), 400–411.
[13] S. Kahraman, M. Fener, O. Gunaydin: "Predicting the sawability of carbonate rocks using multiple curvilinear regression analysis.", International Journal of Rock Mechanics & Mining Sciences, 41(2004), 1123–1131.