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Rock Mechanical Properties: A Review of Experimental Tests and Prediction Approaches

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Abstract

The state of the economy today highlights the requirement for better engineering designs in drilling, well completion, and reservoir production processes. Continuous profiles of rock mechanical properties are required for all of the aforementioned activities. Elastic and strength parameters are two categories that can be used to categorize rock mechanical parameters. Elastic parameters that describe the behavior and tendency of rock to fluctuation or fracture under stress include Young's modulus, bulk module, shear modulus, and Poisson's ratio. To prevent various drilling issues including well kicks pipe sticking, and wellbore instability, it is crucial to understand the elastic properties of reservoir rock. It is therefore conceivable to have an accurate estimation of the rock elastic behavior. The various techniques for estimating the various elastic properties are reviewed in this work. Both a static and dynamic calculation can be done for elastic characteristics. When employing static methods, the elastic modulus can be calculated by measuring it on real cores in a lab using pricy procedures. Whereas well logs are utilized in dynamic methods, a quicker and less expensive technique, to calculate the parameters governing rock elastic properties.

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Introduction

Various drilling issues are still being battled by the oil and gas sector [1]. Many issues exist, such as hole enlargement, fracture, lost circulation, plastic flow, tight holes, stuck pipes, poor hole cleaning, and hole collapse. The majority of these drilling cost-increasing borehole issues are strongly associated with wellbore stability [2]. The imbalance between the rock strengths and generated stress that results from wellbore drilling is the fundamental cause behind these issues [3, 4]. Different rock types in reservoirs react differently to stress. Some reservoirs collapse under extremely high stress, while others break. Understanding a reservoir rock's response to a change in its surroundings can be useful for determining the economics of drilling and finishing wells [5, 6]. Every time a reservoir rock is exposed to a change caused by fluid flow or by pressure variations, it is put under a stress that, if it is too great, could result in irreversible change [7]. Understanding rock strength is essential for analysis and modeling of earth stress, drilling borehole stability, sand production, and hydraulic fracturing [8, 9]. The peak stress at which rock starts to deform during a compress test is referred to as rock strength. There are two basic techniques for determining the strength and failure characteristics of rocks: static and dynamic. Static methods are mostly laboratory experiments employing specialized equipment to measure the mechanical properties of a core sample.

Dynamic approaches often involve calculating the compressional wave velocity (VP) and shear wave velocity (VS), which can be obtained from logs. The mechanical tests are the best indicator of the actual rock strength behavior, but gathering this data is costly and time-consuming because these methods require removing formation core samples and only represent the characteristics of the rock at that specific location [10]

As a result, measurements of rock mechanical characteristics require both laboratory tests and well logging approaches [11]. Instead, it can be found by utilizing pricey methods that involve testing the Young's modulus on real cores in a lab. Following that, the dynamic values obtained from the logs are correlated using the laboratory values. In the literature, a number of correlations were introduced; however, they were all quite specialized and produced very high error rates when used with various cases. Hence, measurements of rock mechanical characteristics require both laboratory tests and well logging approaches. In this paper, we will present a review for the different methods for predicting the rock elastic properties.

2. Static and Dynamic Methods

With the assumption of homogeneity in the geological formation, there are a number of elastic parameters that are frequently utilized in rock mechanics. The behavior of the material is described by these factors, including its potential to deform and fail when subjected to applied stress of a specific magnitude. Young modulus (E), shear modulus (G), Poisson's ratio (νstc), and bulk modulus (K) are the four elastic parameters that are most frequently utilized in solid mechanics [12].

2.1. Young's Modulus

The Young's modulus of rocks can be determined using either destructive or non-destructive methods. In destructive techniques, the material's stress-strain curve is used to calculate the Young's modulus. This curve was created by monitoring the specimen strain throughout compression experiments. These compression tests may be performed in uniaxial or triaxial configurations, and the sample strain may be determined using strain gauges or other comparable devices. The static elastic modulus (Es), which is the Young's modulus determined from the compression (destructive) test, is time-consuming and expensive since it requires high-quality specimens loaded to failure in a uniaxial compression experiment as well as sufficient strain measurement equipment.

Thus, the linear relationship between the applied stress (τ) and the resulting deformation (ε) is expressed by the Young modulus (E):

$$\mathbf{E_s = \tau_a/\varepsilon_a} \qquad (1)$$

Where: τ_a is the axial stress applied and ε_a is the axial strain

Nondestructive procedures are simpler to execute since they require little to no sample preparation and straightforward testing equipment. These can also be utilized in field. As a result, nondestructive procedures are easier, quicker, and more affordable than the uniaxial compression test. Calculating the Young's modulus with an ultrasonic test is the most popular nondestructive method. Both laboratory and field measurements of compressional and shear wave velocities (VP and VS, respectively) can be used to calculate the elastic characteristics [13].

$$E_{\mathrm{Dynamic}} = \rho v_s^2 \left(\frac{3v_p^3 - 4v_s^2}{v_p^2 - v_s^2} \right) \tag{2}$$

Where: E is the dynamic Young’s modulus, Vs and Vp are the shear and compressional ultrasonic wave velocities, respectively, and ρ is the material’s bulk density.

Young’s modulus is different for different rock type; the value depends on the rock properties including porosity, lithology, temperature, pore pressure, Fluid saturation and the rock consolidation.

The accuracy of the Young's modulus calculation can have a significant impact on the outcomes of numerical simulations and modeling for geologic materials. Hammah et al. [14] looked into how Young's modulus affects stress distribution, patterns of rock deformation, and rock failure processes. They observed that the change in Young's modulus, caused a wide range of behaviors in other mechanical parameters, such as stresses. Finite element modeling was used to implement their approach in a number of scenarios.

If the Young's modulus profile surrounding the wellbore is known, the damage can be predicted and assessed. Given that the Young's modulus changes radially with a specified correlation, Nawrocki and Dusseault [15] created a model for calculating the stresses change around the bore hole. Drilling activities caused an alteration in Young's modulus in the radial direction surrounding the wellbore because of stress redistribution and other mechanical factors including cohesion and friction angle. Their model was accurate in describing how the stress regime across the borehole changed throughout drilling and fracturing activities.

Using seismic data, Pigott et al. [16] used the Amplitude Variations with Offset inversion to calculate the rock elastic parameters Poisson's ratio, bulk modulus, shear modulus, and Young's modulus.

To ascertain the Young's modulus of North Sea chalk deposits, Olsen and Fabricius; Nawrocki and Dusseault [15, 17] conducted laboratory experiments. Young's modulus was measured using two different methods: acoustic measurements and a uniaxial compression test with LVDT and strain gauges. When strain gauges were utilized, they discovered that the uniaxial compression test and the acoustic data agreed. They demonstrated that utilizing LVDT in the compression test underestimated the Young's modulus; as a result, it is not advised to use them in experiments of this nature. Young's modulus can be accurately measured using acoustic measurements and uniaxial tests utilizing strain gauges.

Banik et al. [18] calculated the Young's modulus from the seismic data-derived inversion of the acoustic impedance. Only the acoustic impedance was used to derive the Young's modulus; the rock density, shear impedance, or Poisson's ratio were not converted.

According to Howard and Fast [19], the static Young's modulus of shale ranges from 0.1 to 1.0 MPsi, while those of sandstone and limestone range from 8 to 12 MPsi and 2 to 10 MPsi, respectively. These ranges proved that Young's modulus has no set value and that calculating the static Young's modulus is essential for creating geomechanical models.

2.2. Poisson's ratio

The flexibility of rock formation is frequently expressed using Poisson's ratio. Firstly, employing axial and radial deflections of the samples, the triaxial compressive stress test carries out using stress-strain static tests. Then, axial and radial strain relationships lead to the Poisson ratio [20]:

$$\nu_{stc} = -\ \varepsilon_r / \ \varepsilon_a \tag{3}$$

where: ν_{stc} is the Poisson ratio, ε_a is the axial strain, and ε_r is the radial strain, took place during the triaxial compressive stress test.

When axial tension causes stretching as the deformation, the strain is negative. When a material is compressed axially, it contracts and experiences positive strain. Static Poisson's ratio is calculated using equations based on well log data if the core data are unavailable [21]:

$$\nu_{dyn} = \nu_p{}^2 - \nu_s{}^2 / 2\ (\nu_p{}^2 - \nu_s{}^2) \tag{4}$$

For several rock specimens, D'Andrea et al. [22], evaluated the impact of ultrasonic wave transit time on static Poisson's ratio and discovered that the ratio reduces as transit time increases.

Using P-wave and S-wave velocities, Kumar et al. [23] developed a nonlinear regression approach to calculate the static Poisson's ratio.

For materials with various pore size distributions, Phani [24] examined the impact of shear wave velocity on static Poisson's ratio. He discovered that the Poisson's ratio falls with the reduction in S-wave velocity in materials having needle-like and spherical shaped holes.

According to Edimann et al. [25] and Kumar et al. and [23], the rock's porosity increasing causes it to have a greater Poisson's ratio. They created an equation to calculate the static Poisson's ratio.

Al-Shayea [26] examined how static Poisson's ratio values were affected by microcracks and lithological differences. Additionally, he connected the static Poisson's ratio and confining pressure.

Using the linear regression approach, Shalabi et al. [27] connected the static Poisson's ratio to the unconfined compressive strength and rock hardness for shale rocks.

2.3. Shear Modulus

The relationship between shear stress (F/A) and shear strain ($\Delta x/l$) determines shear modulus:

$$\mathbf{G = (F/A)/(\Delta x/L)} \tag{5}$$

Where: G = Shear modulus, F = force, A = area, Δx = transverse displacement, and L = initial length

The response of a material to shear stress is described by the shear modulus, which can be calculated using well logs.

$$G_{dyn} = (13474.45)\frac{\rho_b}{(\Delta t_{shear})^2} \tag{6}$$

2.4. Bulk Modulus

Bulk modulus (K) measures a material's resistance to isotropic volume change (V) under isometric compression (P), i.e., uniform compression in all directions, which expresses how much a rock will deform voluminously under a given amount of tension. It also represents the inverse of the rock compressibility [10].

$$\mathbf{K=\Delta P/[\Delta V/V]} \tag{7}$$

Compressional and shear acoustic wave velocities connected to the bulk density logs were used to calculate the dynamic values of the bulk modulus as shown in Eqs. 8 and 9 [19, 21].

$$K_{dyn} = (13474.45)\rho_b\left[\frac{1}{(\Delta t_{comp})^2}\right] - \frac{4}{3}G_{dyn} \tag{8}$$

$$K_{dyn} = E/3\ (1 - 2v) \tag{9}$$

The above properties can be calculated as a function of porosity. For example, Abbas et al. [28] created correlations (Eqs. 10 through 12) to calculate a sandstone formation's static Young's modulus (E), bulk modulus (K), and shear modulus (G) as a function of porosity:

$$E = 40.476 - 136.79\phi \tag{10}$$

$$K = 20.24 - 54.006\phi \tag{11}$$

$$G = 17.217 - 60.058\phi \tag{12}$$

3. Relationship between Static and Dynamic properties

The reservoir in situ stress-strain situation is more accurately represented by static elastic characteristics [29]. Static elastic parameters are utilized extensively in geotechnical modeling because they are more realistic than dynamic parameters [30]. It is more challenging to measure static elastic parameters than their comparable dynamic properties. This is due to the fact that the static tests are performed using high-quality rock core specimens, which might not be present in all wells. In addition, it is extremely expensive and time-consuming to conduct compression tests and retrieve cores from the entire reservoir portion [31, 32]. Dynamic elastic parameters, on the other hand, can be found from well log data or by ultrasonic tests on core samples. Because to the high cost of extracting core samples and running laboratory tests, only a few number of core samples are frequently retrieved from the depth of interest before a correlation is established between the core and log data. Hence, in order to continuously and accurately anticipate the mechanical characteristics of rocks along a wellbore, it is crucial to understand the connection between dynamic and static parameters [33].

These correlations produced from the log are utilized to validate the dynamic elastic modulus to provide the static modulus across the depth of the reservoir section, as well as from the non-cored locations [31, 34]. Due to the complicated lithology and the limits of these log-derived correlations, they are unable to accurately represent the trend of heterogeneous formations.

Several models and relationships were developed to determine the static Young's modulus as a function of the dynamic Young's modulus in order to get over these restrictions. The generated models were created for a particular rock type and set of circumstances.

As initially reported by Zisman [35] and Ide [36], the dynamic modulus is typically much higher than the static moduli. With soft rocks compared to hard rocks, the discrepancy between the dynamic and static modulus is more obvious [37].

According to Ide [36] and Brace [38], the confining stress, the rock microstructure, the experiment's drainage conditions, the material's heterogeneity, and the effects of anisotropy all have a significant impact on the discrepancy between the static and dynamic modulus. As the rock is compacted, high stresses could seal the microcracks and enhance the velocity of the waves. It will be assumed that the quicker waves have a greater elastic modulus.

Zisman [35] described how the energy loss that a wave pulse can experience when travelling through rock pores (intergranular pores or natural fractures) as a result of reflection and refraction at the fluid/rock interfaces led to the discrepancy between the static and dynamic modulus [39].

To establish a connection between the static and dynamic Young's modulus, several equations have been proposed. Each of these correlations can only be used in certain situations and with certain types of rocks.

Belikov [40] created a correlation to calculate the static Young's modulus from the dynamic one. However, only granite and microcline rocks can be used with their equation. For igneous and metamorphic rocks, a correlation was found by King [41]. While, McCann and Entwisle [42] presented correlation for granite. In addition, Morales and Marcinew [43] developed an equation for static-dynamic modulus for high permeability rocks. Canady [29] created two separate correlations for both hard and soft rocks. Moreover, there are other calculations that can be applied to various types rocks [20, 44, 45].

Elkatatny [46] created an empirical equation for calculating static modulus from wireline log data for various rock types.

Gardner et al. [47], Raymer et al. [48], and Tixier et al. [49] created mechanical properties logs by correlating the in-situ strength with dynamic elastic constants calculated from acoustic and density logs. Anderson et al. [50] and Bruce [51] tried to use the sonic log to forecast the uniaxial compressive strength based on a shale content correction factor and the relationship between the static Young's modulus and the uniaxial compressive strength.

Thus, the calculation of static modulus (Es) from dynamic modulus (Ed) for different rock types has received a great deal of attention, and multiple empirical linear and non-linear equations are referenced in the literature, for example:

$$\mathbf{E_S = a\ E_d + b} \tag{13}$$

$$\boldsymbol{ES = a + (E_d)^b} \tag{14}$$

Where: a and b = material-dependent constants (ranged from a = 0.097 to 0.152 and b from 1.388 to 1.485)

While, [52] presented the below logarithmic equation:

$$\log E_s = A_0 + A_1 \log E_d \quad (15)$$

When dynamic modulus is known, the use of such equations enables the estimation of static. For the lithological type under consideration, several tests should be conducted to calibrate these equations. Numerous empirical correlations to Es prediction from dynamic data are provided in (Table 1)

Table 1: Literature empirical correlations for UCS and E_s from dynamic date

Eq.No.	Lithology	Equation	Reference
16	Igneous and Metamorphic	$E_s = 1.263E_d - 29.5$	[41]
17	Sedimentary	$E_s = 0.74E_d - 0.82$	[53]
18	Soft rocks	$UCS = 2.28 + 4.0189E_s$	[54]
19	Sedimentary	$UCS = 0.278Es^2 + 2.458E_s$	[30]
20	Sedimentary	$E_s = 0.018Ed^2 + 0.422E_d$	[30]
21	Hard Rock E_s>15 Gpa	$E_s = 1.153E_d - 15.2$	[55]
22	Shale	$UCS = 0.77VP^{2.93}$	[56]
23	Shale	$E_s = 0.076VP^{3.32}$	[56]
24	Mudstone	$E_s = 0.103UCS^{1.086}$	[57]
25	Shale	$E_s = 0.0158{E_d}^{2.74}$	[58]
26	Different Rock	$UCS = 2.304VP^{2.43}$	[59]
27	Limestone	$E_s = 0.541E_d + 12.852$	[20]
28	Limestone	$UCS = 2.94(Es^{0.83}/n^{0.088}$	[60]
29	Limestone	$E_s = 0.189\ VP^{3.226}$	[61]
30	Limestone	$E_s = 0.103{E_d}^{1.487}$	[61]
31	Limestone	$E_s = 0.014{E_d}^{1.96}$	[45]
32	Limestone	$E_s = 0.169\ VP^{3.324}$	[45]
33	Limestone	$\mathrm{Log}(\rho E_s) = 1.566 \log(E_d) - 0.702$	[45]
34	Limestone	$\mathrm{Log}(\rho E_s) = 1.479 \log(E_d) - 0.695$	[45]
35	Carbonate	$E_s = 31.5\,VP - 63.7$	[62]
36	Carbonate	$E_s = 74 ln\,VP - 572$	[63]

4. Conclution

The oil and gas industry is still battling a number of drilling-related problems. The majority of these drilling problems that raise drilling costs are closely related to wellbore stability. The underlying cause of these problems is an imbalance between the rock strengths and generated stress as a result of wellbore drilling. For the analysis and modeling of earth stress, drilling borehole stability, sand production, and hydraulic fracturing, it is crucial to comprehend rock strength. Thus, in this paper, We presented and discussed the various experimental tests and prediction approaches for the rock mechanical properties such as Young modulus (E), shear modulus (G), Poisson's ratio (νstc), and bulk modulus (K). we concludes that for the purpose of building geo-mechanical earth models, elastic parameters must be used to evaluate the in-situ stresses of the rock, and to prevent the risks related with oil and gas drilling. In addition, The precise estimation of elastic parameters assists with well site optimization, determining the safe mud weight window, managing wellbore stability, and improving the fracturing operation.

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