Journal of Geotechnology and Energy | vol. 39 | no. 1 | 2022 | pp. 5–13

https://doi.org/10.7494/jge.2022.39.1.5

Dariusz Knez

ORCID: 0000-0003-1028-2497
AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

Herimitsinjo Rajaoalison

ORCID: 0000-0002-4872-0109
AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

Donatille Nkunzi

ORCID: 0000-0003-1850-7304
AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

DRILLING MUD INFLUENCE ON SANDSTONE POROELASTIC PARAMETERS

Date of submission:
14.02.2022

Date of acceptance:
18.02.2022

Date of publication:
31.03.2022

https://journals.agh.edu.pl/jge

Abstract: Perhaps the most critical challenge faced during drilling operations is related to the stability of the well. Additionally, drilling mud plays a crucial role in wellbore stability, as one of its main uses is to support the wellbore wall during the drilling operation. However, ignorance of the effects of drilling mud on the mechanical properties of rock formation can also lead to well failure. The stability of the wellbore is also influenced by pore pressure during the drilling process. The analysis of changes in rock poroelastic parameters after drilling mud saturation was found to be useful regarding the abovementioned issues. Therefore, the measurement of the dynamic Young's modulus, Poisson's ratio and Biot's coefficient of sandstone samples was carried out to determine their trends of variations with confining pressure in different conditions such as dry, water and drilling mud filtrate saturation. The findings indicate that both the dynamic Young's modulus and the Poisson's ratio of the sandstone rock increased after saturation with water and drilling mud filtrate, while the Biot's coefficient was reduced. Furthermore, the velocity of the P wave, the dynamic Young's modulus and the dynamic Poisson's ratio of the sandstone rock were proportional to the confining pressure, while the Biot's coefficient were inversely proportional to the confining pressure. The results imply that effective stress calculation can be influenced by changes in poroelastic parameters established from geophysical measurements, and risk management of wellbore stability stability was increased.

Keywords: drilling mud, rock mechanical properties, Biot's coefficient, acoustic waves, dynamic measurement

1. Introduction

The drilling process is a very sensitive stage in the petroleum industry that influences the efficiency of exploration and production with high capital investments and risks. Better understanding of the formation that is being drilled is one way to avoid complications during this process. For example, knowing the effect of drilling mud on the geomechanical properties of rock formation is helpful in maintaining the stability of the well and minimizing complications during drilling operation. The disadvantage is that the chemical composition of the drilling fluid should be taken into account to avoid the chemomechanical interaction with the reservoir. Young's modulus, Poisson's ratio, and Biot's coefficient are fundamental parameters that effectively influence porous media. The pore pressure in the well is a key variable to maintain during the drilling process. The maintenance of well stability during drilling operations in oilfields requires knowledge of rock deformation and pore pressure behaviour [1]. Based on the values of parameters calculated near the wellbore stresses, controllable factors and proppants can be selected properly [2, 3]. The exact estimation of the subsurface pore pressure is crucial for successful well design and the reduction of operational costs and risks during the drilling process [4].

Drilling and production operations take place in porous media such as reservoirs saturated with different types of fluids including oil, gas, condensate, and water. For example, the compressibility of the rock decreases the pore pressure when fluid is injected into the rock. Permeability also influences the change in pore pressure where the latter increases in the presence of rock saturated with an impermeable liquid, while there is no occurrence of variation in pore pressure when the rock is permeable because the volume of injected water is equal to the volume flowing from the rock [5]. Therefore, the changes in pore pressure and volume of porous formation are the results of activities undertaken related to hydrocarbon production or even sequestration of carbon dioxide. These changes are very important because they can lead to formation compaction and subsidence expressed on the surface [6–8]. Therefore, understanding the Biot's coefficient that contributes to these changes is very important because this parameter is required in order to be able to predict the propagation of the pore pressure through the skeleton material. Therefore, the measurement of the Biot's coefficient is an important parameter for determining the poroelastic effect on porous rock, as it remains the essential poroelastic characteristic used to determine the effect of pore pressure that leads to a change in the effective stress of the rock formation and has a significant impact on the wellbore stability [9].

Overbalanced and underbalanced pressure are the most common cases encountered during drilling, especially in horizontal wells. Drilling mud density is used as a tool to balance wellbore pressure with formation pressure to avoid the loss of formation damage and wellbore breakouts [10, 11]. Formation damage is a usual circumstance that occurs at any stage of the oilfield cycle. It is caused by many factors such as clay swelling, the presence of solid hydrocarbons, and mainly filtrate blockage. This problem contributes to the low efficiency of the well. Therefore, the formulation of the drilling fluid should comply with the minimization of the invasion of the drilling mud solid, filtrate, and polymers into the formation. This is done by taking into account the amount of bridging agents and the viscosifier [12].

Therefore, understanding rock formation is a key factor in addressing these challenges, and this article describes the experimental results of the dynamic Young's modulus, Poisson's ratio and Biot's coefficient of sandstone rock formation as a function of hydrostatic stress using an acoustic velocity system in dry, water, and mud saturation.

2. Methodology

The studies of mechanical rock properties in this work are done dynamically using acoustic waves. The values of primary and secondary wave velocity and the density of the specimen are used to calculate these mechanical rock parameters. It is important to note that the dynamic moduli of the rock are different from the static moduli due to some assumptions before any calculation, such as homogeneous, isotropic and perfect elastic of the rock being studied, which is not always true in most cases [13]. The dynamic moduli of fine-grained and igneous rocks, as well as sedimentary rocks are higher than static moduli, including Young's modulus, shear modulus, and Poisson's ratio [14]. Furthermore, King's experimental studies on the anisotropy and nonlinearity of the mechanical behavior of rocks [14] supported such a differentiation between dynamic and static moduli due to randomly oriented cracks within the specimen. Therefore, the unconformities between the results of the measurement of dynamic and static elastic properties are mainly related to the variation of the lithology and microcrack distribution of microcracks in rock materials [15–17].

The dynamic mechanical properties of the rock were calculated using the ratio between the velocities of the P and S waves of the elastic wave through rock samples, using Newton's second law of motion and Hooke's law [18]. Therefore, the correlation between dynamic and static moduli depends on the adaptiveness of the propagation of elastic wave and Hooke's law, as Newton's second law is always applicable. Multiple studies have been conducted on P-wave velocity, as it is very useful for various engineering purposes, such as weathering depth related to construction and formation saturation related to drilling process [19–21]. The sound velocity through the rock sample is affected by the rock type, density, grain size and shape, anisotropy, porosity, fluid content, stress, temperature, and pre-existing microfracture within the specimen. Furthermore, the effect of water content on the ultrasonic velocities through sandstone samples has been investigated by Wyllie et al., and they found that the velocity is decreasing as a function of saturation [22]. In addition, Kahraman derived some empirical relationship between the compressive velocity of dry and water-saturated rocks [23]. In the present work, the effects of different types of saturation fluids as well as the increase of confining pressure on the velocities of the compressional wave through sandstone rock will be investigated, together with the poroelastic parameters that relate to them.

An acoustic velocity system (AVS) is an apparatus used to measure the dynamic mechanical properties of rock samples using acoustic waves [24]. It is made up of a panel, core holder, pressure pipes, acoustic transducers and receivers, switch box, digital oscilloscope, hand pump, heating mantle, and a computer for data storage and analysis. The plugs were inserted into the coreholder in condition that axial is parallel (Fig. 1). A confining pressure of 7 to 45 MPa were applied to the system while the pore pressure valve was opened, which meant it was equal to atmospheric pressure. Thus, the pore pressure was constant throughout the measurement process.

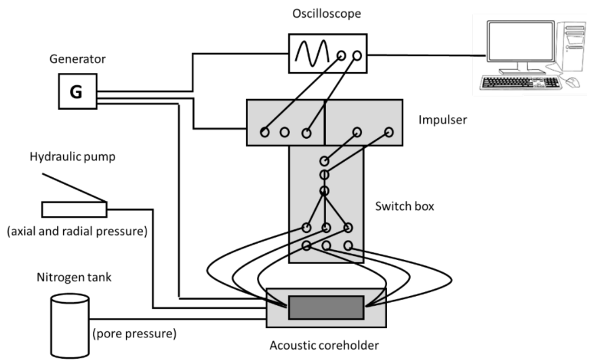

Fig. 1. AVS 1000 apparatus [25]

Acoustic wave velocities were measured to obtain geomechanical properties such as Young's modulus, Poisson's ratio. The low frequency transmitter and receiver were placed at each edge of the core holder and the time flight of P and S waves through the samples was recorded in microseconds [26]. Dynamic Young's modulus (E), Poisson's ratio (ν) and the bulk modulus were calculated using wave velocities and the density of sample using Equations (1), (2) and (3) [18, 27]:

$$\nu = \frac{V_P^2 - 2V_S^2}{2V_P^2 - V_S^2} \tag{1}$$

$$\mathrm{E} = \frac{\rho V_S^2 \left(3V_P^2 - 4V_S^2\right)}{V_P^2 - V_S^2} \tag{2}$$

$$\mathrm{K} = \frac{\mathrm{E}}{3\left(1 - 2\nu\right)} \tag{3}$$

where ν is the dynamic Poisson's ratio [–], E is the dynamic Young's modulus of the rock [Pa], ρ is the rock density (kg/m^3), K is the bulk modulus of the rock [Pa], V_P is the compressional wave velocity [m/s], and V_S is the shear wave velocity [m/s].

The Biot's coefficient is calculated using the relationship between the rock and the bulk modulus. The dynamic bulk modulus is calculated from the P and S wave velocities obtained under in situ loading conditions. Biot's coefficient means the decrease of pore fluid induced by solid grains compaction. Biot's coefficient can be determined by Equation (4) [6, 7, 28, 29]:

$$\alpha = 1 - \frac{K_S}{K_O} \tag{4}$$

where K_S is the bulk modulus of the rock [Pa], and K_O is the bulk modulus [Pa]. K_S can be calculated using Equation (5), while K_O is measured in hydrostatic load where the pore pressure must be equal to the confining pressure so that only the solid grains carry the confining pressure [24, 27]. Taking into account the homogeneity and isotropic nature of the samples studied, we used $\mathrm{K_O}$ = 85 GPa, as it represents the volumetric bulk modulus for sandstone minerals [30].

$$K_S = \rho_{dry} V_P^2 - \frac{4}{3}\rho_{dry} V_S^2 \tag{5}$$

It is important to note that the value of the dynamic bulk modulus is different from the static bulk modulus due to the different strain amplitude of the experimental techniques [18, 31, 32].

Experimental studies

The samples studied in this paper are cored from sandstone rock from an outcrop. The length and diameter of the samples were 40 mm ±1 mm and 38 mm, respectively. The core samples were cut and polished according to the requirements to have a smooth surface, so the coupling between the transducer and the receiver will be good and the transit time measurement of the arrival time of the waves will be more accurate, and the mechanical error due to the geometry of the sample will be minimized (Fig. 2). It is important to have as low a measurement error as possible because the uncertainty of the investigated poroelastic parameters influences many petroleum projects such as hydraulic fracturing [33, 34]. The P-wave velocity is then derived from the distance where the wave traveled (the sample length), divided by the pulse transit time. The samples obtained were kept in an oven at 70°C for at least a day to be dried and the weight of each sample was measured.

Fig. 2. Prepared core samples

Later, they were saturated with distilled water to calculate the bulk density and porosity. Water and drilling mud were used to saturate the samples in order to understand how the poroelastic properties behave with different types of fluid used, under incrementation of confining pressure. The results found are of 2.63 g/cm^3 and 13% respectively.

In all stages of the life of the well, including drilling, completion, stimulation, flow tests, production, and depletion, its stability is very important. During drilling operations, this is mainly concerned with the composition of the drilling mud and its density, so that the integrity of the wellbore is maintained without losing the drilling fluid. Failure occurs easily if one does not pay attention to the characteristics of the drilling mud and its effects on the formation being drilled [35, 36]. In this investigation, the drilling mud filtrate with chemical composition in Table 1 was used to saturate the sample to investigate its effect on the rock mechanical properties of the core samples under confining pressure.

Such research is very important to maximize the understanding of formation characteristics such as dynamic mechanical properties, which is necessary to formulate the mud weight window during drilling, so that the reservoir is economically productive and the costly problems induced by wellbore instabilities are reduced [37].

Table 1. Drilling mud composition

Material	Description	Quantity [%]
CMC	viscosifier	1.0
KCl	clay stabilizator	1.5
PHPA	–	0.3
$CaCO_3$	alkalinity control/ mineral bridging agent	10.0
Organic bridging agent	–	1.0

3. Results and discussions

Understanding the stability issues during the drilling and production process is crucial, especially in case difficult geological conditions are encountered such as cross faults. The main cause of disasters and difficulties during drilling is related to poor understanding of the formation being drilled and the lack of adequate chemicals used to formulate the drilling mud. Worldwide, such disasters cost nearly 8 billion USD per year [38]. As part of preventive solutions, this study helps to understand the behaviour of the dynamic poroelastic parameters of the sandstone under variation of the confining pressure after saturation with water and drilling mud.

The first result shows the variation of the compressional velocity under the changed conditions. Next, the relationship between dynamic poroelastic parameters and confining pressure will be discussed, followed by an explanation of the possible reasons for the differentiation between the recorded values from water and mud-saturated samples. One of utilities of the understanding the dynamic mechanical properties of rock is its application to seismic response analysis. Dynamic shear strength and static strength are slightly different for hard rock, such as gneiss, but not necessarily the same for soft rock, such as sandstone, because it is affected by external and internal conditions, such as roughness, hardness, degree of weathering, and grain sizes [17, 24]. The compressional velocity through dry, water-saturated and mud-saturated sandstone samples, under increased confining pressure, is presented in Figure 3.

The increase in confining pressure results in linear increase of P-wave velocity, which is supported by the coefficient correlation of 0.94 for dry samples, while 0.86 and 0.99 for water and mud saturated samples, respectively. In addition, fluid saturation does affect the speed of the compression wave. It increases to 20% for water saturation and about 30% for drilling mud saturation (Fig. 3). It also shows the effects of saturation as well as the type of fluid on the velocity propagation of compressional waves through porous media. The effect of the saturation of the water and mud filtrate on the dynamic mechanical properties of the sandstone samples at room temperature is shown in Figure 4.

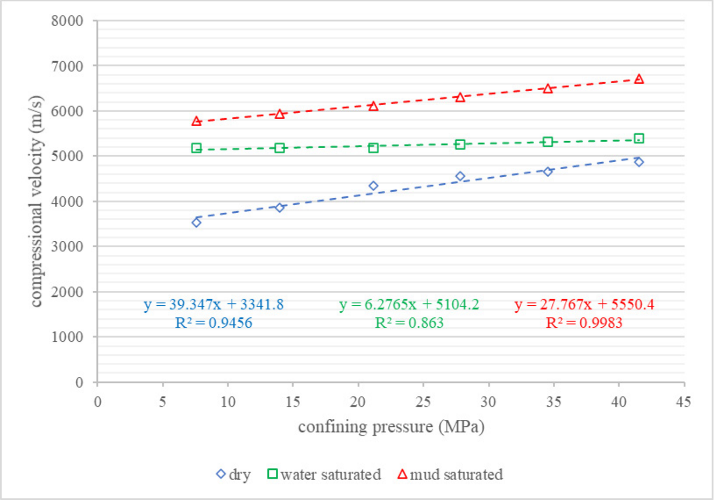

Fig. 3. Compressional velocity of dry, water-saturated and drilling mud saturated sandstone versus confining pressure

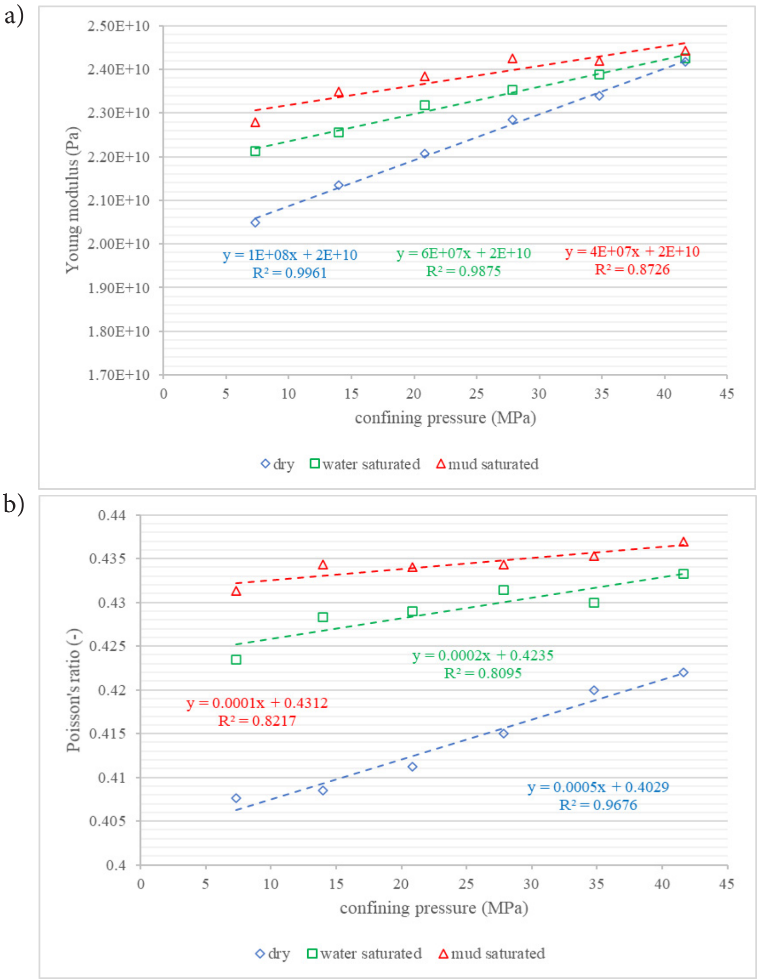

Fig. 4. Variation of Young's modulus (a) and Poisson's ratio (b), for dry, water saturated, and mud saturated sandstone versus confining pressure

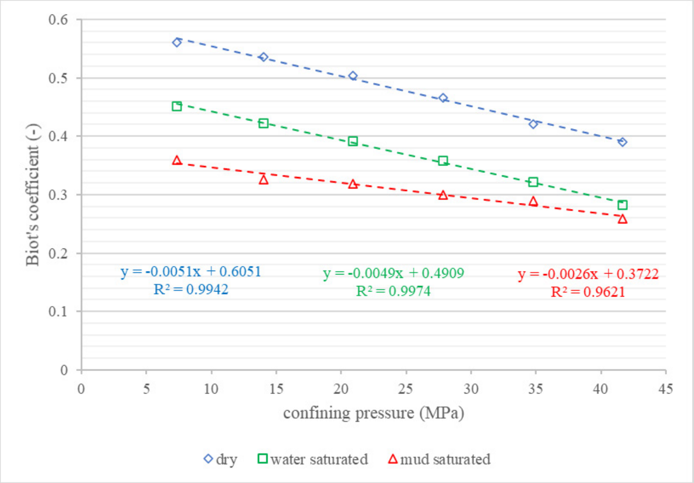

Fig. 5. Variation of the Biot's coefficient for dry, water-saturated, and mud-saturated sandstone versus confining pressure

The increase in the dynamic Young's modulus occurred after the sample was saturated with water. The results show that the sandstone core samples exhibit a slight increase in the Young's modulus behaviour up to 4%, 6.50% (Fig. 4a) and Poisson's ratio up to 5%, 6.10% (Fig. 4b) after being saturated with water and drilling mud filtrate, respectively. The increase is associated with the high viscosity of the drilling mud, which significantly increases the velocities of the P and S waves, which in turn increases both the Young's modulus and Poisson's ratio [39]. This contradicts what other studies have reported, namely that the drilling fluid weakens the rock due to the invasion of the loss of fluid with starch contained in the drilling mud [40] and the long exposure (24 hours) of samples with polymers that make up the drilling fluid, and this destroys the stiffness of the rock [41]. It is worth mentioning that the increase in the dynamic Young's modulus in this research does not mean an increase in the static Young's modulus value. Thus changes in the dynamic poroelastic parameters due to saturation could be different for static measurements. The Poisson's ratio increased slightly subsequently with the saturation of water and water-based drilling mud. Furthermore, the positive correlation between the Poisson's ratio, the Young's modulus, and confining pressure is supported by the significant correlation coefficient presented in Figure 4. In Figure 5, water saturation significantly decreased the dynamic Biot's coefficient of core samples by 23%.

Furthermore, the drilling of the mud filtrate has presented an important depletion of the Biot's coefficient of up to 35.40%. The negative linear correlation between Biot's coefficient and confining pressure is supported by the good correlation coefficient of 0.99 for dry samples, while 0.99 and 0.96 for saturated water and mud samples, respectively.

4. Conclusions

The effects of water and mud saturation on the poroelastic parameters of sandstone rock under increased confining pressure were carried out using acoustic waves. Laboratory results have shown the following:

1. The dynamic elastic modulus tends to increase when the rock is filled with fluids such as drilling mud and water due to the viscosity coupling phenomenon because the saturating drilling mud has high viscosity, which leads to an increase in wave velocities.
2. Samples filled with drilling mud slightly increase their dynamic Poisson's ratio and the Young's modulus when hydrostatic stress increases due to closure of microfractures within the sample and decreasing porosity.
3. When stress increases, there is a clear tendency to reduce the dynamic Biot's coefficient of cores saturated with water and drilling mud filtrate.
4. The Young's modulus and Biot's coefficient plots show convergence behaviour when hydrostatic stress increases.
5. An increase in the dynamic elastic modulus due to water and drilling mud saturation does not necessarily mean an increase in the static elastic modulus.

Authors' Contributions: All authors contributed to the acquisition of data and the writing of this manuscript. Conceptualization: Dariusz Knez, Herimitsinjo Rajaoalison; methodology: Dariusz Knez, Donatille Nkunzi; software: Herimitsinjo Rajaoalison, Donatille Nkunzi; validation: Dariusz Knez, Donatille Nkunzi, Herimitsinjo Rajaoalison; formal analysis, Dariusz Knez, Donatille Nkunzi, Herimitsinjo Rajaoalison; investigation: Donatille Nkunzi, Herimitsinjo Rajaoalison; resources: Dariusz Knez; data curation: Donatille

Nkunzi, Herimitsinjo Rajaoalison; writing – original draft preparation: Dariusz Knez, Donatille Nkunzi, Herimitsinjo Rajaoalison; writing – review and editing: Dariusz Knez, Donatille Nkunzi, Herimitsinjo Rajaoalison; supervision: Dariusz Knez; project administration: Dariusz Knez; funding acquisition: Dariusz Knez.

Funding: This research was funded by the AGH University of Science and Technology subsidy 16.16.190.779 and AGH–UNESCO.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Suarez-Rivera R., Deenadayalu C., Chertov M., Hartanto R.N., Gathogo P., Kunjir R.: *Improving Horizontal Completions on Heterogeneous Tight-Shales*. Journal of Petroleum Technology, vol. 64, 2012, pp. 126–130. https://doi.org/10.2118/1012-0126-JPT.

[2] Knez D., Wiśniowski R., Owusu W.A.: *Turning Filling Material into Proppant for Coalbed Methane in Poland – Crush Test Results*. Energies, vol. 12, 2019, 1820. https://doi.org/10.3390/en12091820.

[3] Knez D., Calicki A.: *Looking for a New Source of Natural Proppants in Poland*. Bulletin of the Polish Academy of Sciences. Technical Sciences, vol. 66, no. 1, 2018, pp. 3–8. https://doi.org/10.24425/119052.

[4] Mukerji T., Dutta N., Prasad M., Dvorkin J.: *Seismic Detection and Estimation of Overpressures. Part I: The rock physics basis*: CSEG Recorder, vol. 27, no. 7, 2002, pp. 34–57.

[5] Kim K., Vilarrasa V., Makhnenko R.Y.: *CO_2 Injection Effect on Geomechanical and Flow Properties of Calcite-Rich Reservoirs*. Fluids, vol. 3, no. 3, 2018, 66. https://doi.org/10.3390/fluids3030066.

[6] Biot M.A.: *General Theory of Three-Dimensional Consolidation*. Journal of Applied Physics, vol. 12, 1941, pp. 155–164. https://doi.org/10.1063/1.1712886.

[7] Cheng A.-D.: *Material Coefficients of Anisotropic Poroelasticity*. International Journal of Rock Mechanics and Mining Sciences, vol. 34, 1997, pp. 199–205. https://doi.org/10.1016/s0148-9062(96)00055-1.

[8] Wang H.F.: *Quasi-Static Poroelastic Parameters in Rock and Their Geophysical Applications*. In: R.C. Liebermann, C.H. Sondergeld (eds.), *Experimental Techniques in Mineral and Rock Physics*, Pageoph Topical Volumes, Birkhäuser, Basel, pp. 269–286. https://doi.org/10.1007/978-3-0348-5108-4_5.

[9] Luo X., Were P., Liu J., Hou Z.: *Estimation of Biot's Effective Stress Coefficient from Well Logs*. Environmental Earth Sciences, vol. 73, 2015, pp. 7019–7028. https://doi.org/10.1007/s12665-015-4219-8.

[10] Sloan J.P., Brooks J.P., Dear III S.F.: *A New, Nondamaging, Acid-Soluble Weighting Material*. Journal of Petroleum Technology, vol. 27, 1975, pp. 15–20.

[11] Rajaoalison H., Knez D.: *Current Trends in Land Subsidence of the North-Central Part of Poland Using DInSAR Technique*. E3S Web Conferences, vol. 266, 2021, 03006. https://doi.org/10.1051/e3sconf/202126603006.

[12] Vryzas Z., Matenoglou G., Kelessidis V.C.: *Assessment of Formation Damage Potential of Novel Drilling Fluids via Integration of Fluid Loss Data with Filter Cake Quality and Filtrate Core Penetration Depth from NMR and MRI*. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, November 2017, SPE-188544-MS, Society of Petroleum Engineers, 2017. https://doi.org/10.2118/188544-MS.

[13] Ide J.M.: *The Elastic Properties of Rocks: A Correlation of Theory and Experiment*. Proceedings of the National Academy of Sciences of the United States of America, vol. 22, no. 8, 1936, pp. 482–496. https://doi.org/10.1073/pnas.22.8.482.

[14] Tuman V.S., Alm R.F.: *Dynamic and Static Elastic Properties*. SPE-603-MS, Society of Petroleum Engineers, 1963.

[15] King M.S.: *Static and Dynamic Elastic Moduli of Rocks under Pressure*. Paper presented at the 11th U.S. Symposium on Rock Mechanics (USRMS), Berkeley, California, June 1969, ARMA-69-0329, American Rock Mechanics Association, 1969.

[16] Al-Shayea N.A., Khan K.: *Dynamic and Static Moduli of Limestone Rock from Saudi Arabia*. In: W. Sijing, F. Bingjun, L. Zhongkui (eds.), *Frontiers of Rock Mechanics and Sustainable Development in the 21st Century*. A.A.Balkema, 2001, pp. 109–113.

[17] He J., Ling K., Wu X., Pei P., Pu H.: *Static and Dynamic Elastic Moduli of Bakken Formation*. Paper presented at the International Petroleum Technology Conference, Beijing, China, March 2019, IPTC-19416-MS, 2019. https://doi.org/10.2523/IPTC-19416-MS.

[18] Fjær E.: *Static and Dynamic Moduli of a Weak Sandstone*. Geophysics, vol. 74, 2009, pp. 103–112. https://doi.org/10.1190/1.3052113.

[19] Christaras B.: *P-Wave Velocity and Quality of Building Materials*. In: E. Yüzer, H. Ergin, A. Tugrul (eds.), *Industrial minerals and building stones: IMBS 2003: September 15–18, 2003 Istanbul Turkey*. IAEG, Istanbul 2003, pp. 295–300.

[20] Christaras B., Mariolakos I., Foundoulis J., Athanasias S., Dimitriou A.: *Geotechnical Input for the Protection of Some Macedonian Tombs in Northern Greece*. In: *Proceedings 4th International Symposium on the Conservation of Monuments in the Mediterranean: new concepts, technologies and materials for the conservation and management of historic cities, sites and complexes: Rhodes, 6–11 May 1997*. Technical Chamber of Greece, Athens 1997, pp. 125–132.

[21] Zezza F.: *Evaluation Criteria of the Effectiveness of Treatments by Non Destructive Analysis*. In: *Proceedings of the 2nd Course of CUN University. School of Monument Concervation*. Heraklion 1993, pp. 198–207.

[22] Wyllie M.R.J., Gregory A.R., Gardner L.W.: *Elastic Wave Velocities in Heterogeneous and Porous Media*. Geophysics, vol. 21, 1956, pp. 41–70. https://doi.org/10.1190/1.1438217.

[23] Kahraman S.: *The Correlations between the Saturated and Dry P-Wave Velocity of Rocks*. Ultrasonics, vol. 46, 2007, pp. 341–348. https://doi.org/10.1016/j.ultras.2007.05.003.

[24] Rajaoalison H., Zlotkowski A., Rambolamanana G.: *Mechanical Properties of Sandstone Using Non-Destructive Method*. Journal of Mining Institute, vol. 241, 2020, pp. 113–117. https://doi.org/10.31897/PMI.2020.1.113.

[25] Knez D., Rajaoalison H.: *Discrepancy between Measured Dynamic Poroelastic Parameters and Predicted Values from Wyllie's Equation for Water-Saturated Istebna Sandstone*. Acta Geophysica, vol. 69, 2021, pp. 673–680. https://doi.org/10.1007/s11600-021-00543-3.

[26] Rao M.V.M.S., Prasanna Lakshmi K.J., Sarma L.P., Chary K.B.: *Elastic Properties of Granulite Facies Rocks of Mahabalipuram, Tamil Nadu, India*. Journal of Earth System Science, vol. 115, 2006, pp. 673–683. https://doi.org/10.1007/s12040-006-0005-z.

[27] Rajaoalison H., Knez D., Złotkowski A.: *Zmiany dynamicznych właściwości mechanicznych piaskowca istebniańskiego nasyconego solanką pod wpływem temperatury i naprężenia* [*Changes of dynamic mechanical properties of brine-saturated Istebna sandstone under action of temperature and stress*]. Przemysł Chemiczny, t. 98, nr 5, 2019, pp. 801–804. https://doi.org/10.15199/62.2019.5.22.

[28] Franquet J.A., Abass H.H.: *Experimental Evaluation of Biot's Poroelastic ParameterThree Different Methods*. Paper presented at the Vail Rocks 1999, The 37th U.S. Symposium on Rock Mechanics (USRMS), Vail, Colorado, June 1999, ARMA-99-0349, American Rock Mechanics Association, 1999.

[29] Salemi H., Iglauer S., Rezagholilou A., Sarmadivaleh M.: *Laboratory Measurement of Biot's Coefficient and Pore Pressure Influence on Poroelastic Rock Behaviour*. The APPEA Journal, vol. 58, no. 1, 2018, pp. 182–189. https://doi.org/10.1071/AJ17069.

[30] Korsnes R., Christensen H.F., Trads N., Hiorth A., Madland M.V.: *Measuring the Biot Stress Coefficient and Its Implications on the Effective Stress Estimate*. Paper presented at the 47th U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, California, June 2013, ARMA-2013-282, American Rock Mechanics Association, 2013.

[31] Alam M.M., Borre M.K., Fabricius I.L., Hedegaard K., Røgen B., Hossain Z., Krogsbøll, A.S.: *Biot's Coefficient as an Indicator of Strength and Porosity Reduction: Calcareous Sediments from Kerguelen Plateau*. Journal of Petroleum Science and Engineering, vol. 70, 2010, pp. 282–297. https://doi.org/10.1016/j.petrol.2009.11.021.

[32] Alam M.M., Christensen H.F., Fabricius I.L.: *Effective Stress Coefficient and Biot's Coefficient of Chalk from the Valhall Field, North Sea*. Paper presented at the EUROPEC/EAGE Conference and Exhibition, Amsterdam, The Netherlands, June 2009, SPE-121795-MS, Society of Petroleum Engineers, 2009. https://doi.org/10.2118/121795-MS.

[33] Quosay A.A., Knez D., Ziaja J.: *Hydraulic Fracturing: New Uncertainty Based Modeling Approach for Process Design Using Monte Carlo Simulation Technique*. PLOS ONE, vol. 15, 2020, e0236726. https://doi.org/10.1371/journal.pone.0236726.

[34] Quosay A.A., Knez D.: *Sensitivity Analysis on Fracturing Pressure Using Monte Carlo Simulation Technique*. Oil Gas: European Magazine, vol. 42, iss. 3, 2016, pp. 140–144 .

[35] Ramos G.G., Wilton B.S., Polillo A.F.: *Usage and Applicability of Pseudo-3D Stress Analysis in Borehole Stability Problems in Petroleum Drilling and Production Operations*. Paper presented at the 2nd North American Rock Mechanics Symposium, June 19–21, 1996, ARMA-96-1067, American Rock Mechanics Association, 1996.

[36] Peng S., Fu J., Zhang J.: *Borehole Casing Failure Analysis in Unconsolidated Formations: A Case Study*. Journal of Petroleum Science and Engineering, vol. 59, iss. 3–4, 2007, pp. 226–238. https://doi.org/10.1016/j.petrol.2007.04.010.

[37] Darvishpour A., Cheraghi Seifabad M., Wood D.A., Ghorbani H.: *Wellbore Stability Analysis to Determine the Safe Mud Weight Window for Sandstone Layers*. Petroleum Exploration and Development, vol. 46, iss. 5, 2019, pp. 1031–1038. https://doi.org/10.1016/S1876-3804(19)60260-0.

[38] Charlez P.A.: *The Concept of Mud Weight Window Applied to Complex Drilling*. Paper presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, October 1999, SPE-56758-MS, Society of Petroleum Engineers, 1999. https://doi.org/10.2118/56758-MS.

[39] Khazanehdari J., Sothcott J.: *Variation in Dynamic Elastic Shear Modulus of Sandstone upon Fluid Saturation and Substitution*. Geophysics, vol. 68, 2003, pp. 472–481. https://doi.org/10.1190/1.1567213.

[40] Cherblanc F., Berthonneau J., Bromblet P., Huon V.: *Influence of Water Content on the Mechanical Behaviour of Limestone: Role of the Clay Minerals Content*. Rock Mechanics and Rock Engineering, vol. 49, 2016, pp. 2033–2042. https://doi.org/10.1007/s00603-015-0911-y.

[41] Lai B., Liang F., Zhang J., Li L., Liu H., Al-Muntasheri G.: *Fracturing Fluids Effects on Mechanical Properties of Organic Rich Shale*. Paper presented at the 50th U.S. Rock Mechanics/Geomechanics Symposium, Houston, Texas, June 2016, ARMA-2016-180, American Rock Mechanics Association, 2016.