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ORIGINAL ARTICLE

Determination of cohesion and friction angle on sedimentary rock based on geophysical log

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Abstract Despite the application of numerous geophysical methods in interpreting lithology, only a few are able to predict the mechanical properties of rocks correctly. It is also difficult to obtain data on mechanical rock properties for laboratory testing because it is expensive and requires full core drilling. Conversely, obtaining data of geophysical log is relatively easier because it is quite abundant due to the exploration in open hole and full core drilling. The mechanical properties will be very helpful for analysis, assuming it is easily determined by the geophysical approach. This research aims to model the relationship between mechanical properties and geophysical log data. Data on short density and gamma-ray were collected from laboratory testing known as ASTM and by measuring the boreholes. The data collected were then analyzed to determine the cohesion and friction angle. Specific analysis was carried out on clastic sedimentary rocks with low mechanical properties. The clastic sedimentary rocks are composed of mostly fine-grained to sand-sized quartz minerals. The analysis method was used to determine the relationship between the variables by performing simple linear regression. The result showed that geophysical log data's prediction model of mechanical properties produced an error of 19.71% to 56.14%. Furthermore, the mechanical properties and geophysical log data did not have a strong correlation. Therefore, it is recommended to conduct laboratory testing on the rock samples to determine their mechanical properties. This is possibly performed by multiplying samples with the same geological characteristics to produce a better distribution of data in statistical analysis.

Article highlights

1. The prediction mechanical properties of sedimentary rock can be determined with the geophysical method.
2. The mechanical properties will be very helpful for analysis, assuming it is easily determined by the geophysical approach.
3. Mechanical properties of fine-grained sedimentary rocks do not strongly correlate with the values of long spaced density (LSD), short spaced density (SSD), and gamma-ray.

Keywords Friction angle · Cohesion · Geophysical log · Material properties · Lab test · Sedimentary rock

1 Introduction

In accordance with the current technological advances, geophysical logging and elastic modulus determinations, also known as ISRM, realized based

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on laboratory testing, are used to interpret rock layers (Maákowski and Ostrowski 2017) and predict their mechanical properties. Sonic log data have a moderate-to-strong degree of correlation with uniaxial compressive strength (UCS) values (Zhou and Guo 2020). Meanwhile, electrical resistivity and Young's modulus are strongly correlated in clastic sediments (Yasir et al. 2018). In shale rocks, gamma-ray and density log are used to determine Young's bulk and shear modulus, including Poisson's ratio, besides these attributes have a strong relationship with depth (Parapuram et al. 2017). A research carried out by Al-Kattan and Al-Ameri (2012) stated that sonic and density logs strongly correlate with mechanical properties, namely rock strength, Poisson's ratio, and dynamic elastic modulus, which are measured in the laboratory based on the realized samples. Elastic static sandstones have a perfect relationship with elastic modulus in accordance with artificial neural networks (ANN), proven by the correlation degree of 0.995. A strong relationship exists between elastic modulus and UCS with a correlation degree that is greater than 0.8, although the resulting values vary in previous studies (Share 2018; Mahmoud et al. 2019). However, a detailed explanation of the tested rock characteristics is required to clarify it from previous research, and the nano-seismic monitoring system is also used to identify subsurface rocks' behavior (Fiorucci et al. 2017).

Several factors influence ultrasonic wave velocity, such as density, rock type and mass, grain shape and size, porosity, anisotropy, pore water, confining pressure, and temperature. Additionally, it is also affected by weathering, alteration zone, bedding plane, and joint properties, including fill material, hardness, water, strike, and dip.) (Kahraman et al. 2007). Shear (S-wave) and compressional wave (P-wave) velocities are linearly related for both water-saturated and dry clastic silicate sedimentary rocks, as stated by Castagna et al. (1985) (Altindag 2012). These are also dependent on porosity (void size and pore size distribution) and anisotropy of material particles (Kahraman et al. 2007) (Gaviglio 1989).

Furthermore, (Rodríguez-Sastre and Calleja 2006) stated that elastic modulus depends on ultrasonic wave velocity, and a linear relationship exists between the inclination angle of foliation and the dynamic elastic constant, although this was less visible in Poisson's ratio. (Nourani et al. 2017) assessed rock mass properties using P-wave velocity in Choghart iron mine. The result showed that rock mass rating (RMR) and Q value strongly correlate with compressional velocity obtained from either the field or laboratory. (Fei et al. 2016) analyzed the linear correlation between dynamic and static elasticity of rocks under the same condition and reported that the dynamic Young's modulus is greater than the static. (Khandelwal 2013) investigated the relationship between mechanical properties of igneous rocks and P-wave velocity and reported the existence of an empirical correlation between both attributes, where compressional wave velocity correlates with density and porosity (Rahmouni et al. 2013). However, this analysis does not confirm the modulus elasticity value based on laboratory testing. Therefore, its determination has not been verified according to the standard measurement, however, it is possibly affected by temperature (Yang et al. 2021).

P and S-waves strongly correlate with the rocks' mechanical properties, such as density, unconfirmed compressive strength (UCS), and elastic modulus (Bieniawski and Bernede 1979). The research of the relationship has been carried out under dry and saturated conditions, and it was proven that these properties correlate with P and S-wave velocities (Share 2018). The 2 studies failed to explain in detail the rock characteristics used in the test. Density, P-wave velocity, and UCS data related to sandstone samples obtained from lignite mines (NLC) are higher compared to those from coal mines (SCCL) (Chary et al. 2006). Porosity affects UCS, where the lower the porosity, the higher the rock density, and vice versa. Additionally, an increase in density also increases the UCS, therefore, all these attributes, including VS have a positive relationship (Cheng and Hu 2003).

Geotechnical properties of the rock are predicted by utilizing geophysical log with Prompt Gamma Neutron Activation Analysis (PGNAA) method (Borsaru et al. 2005). Meanwhile, a geophysical log provides subsurface data records in a borehole by detecting radioactive signals present in the rock. Radioactivity decomposes atomic nuclei spontaneously, thereby emitting alpha and beta particles, or gamma radiation. These are also referred to as radioactive rays, while the substances emitting radioactive rays are radioactive substances. Furthermore, the geophysical log is used to measure and record physical properties and lithology at each depth (Reeves 1971). The continuous data recorded by logging is a wireline log that investigates the response to rock properties variations in a borehole. Logging speed affects the quality of generated data, therefore, it needs to be adjusted to the rock characteristics (Priest et al. 2013). However, highly accurate geophysical logs tend to read up to a thin formation layer (Belougne et al. 1996). Since delay affects data quality, optimal logging speed needs to adopt a mathematical approach in line with the acquisition process (Kerzner 1998). Another method used to identify subsurface conditions is the Multichannel Analysis of Surface Waves (MASW). This approach is quite good at identifying both fresh and weathered (Hidden) subsurface rocks (Hiden and Teguh., Minardi, Suhayat., Taurida, Alfina., Muhajirah., 2018).

Under appropriate conditions, density log accurately measures bulk density, estimates porosity (Pickel et al. 2017), and identifies rock formation (McCall and Gardner 1982). It uses a radioactive ray source that emits gamma rays from a measuring device with a certain energy intensity realized through rock formation to measure its density (Harsono 1997). Rocks consist of mineral grains composed of atoms containing protons and electrons. Furthermore, when gamma-ray particles hit these electrons, the resultant collision causes its energy to reduce, and this is measured with a detector at a specific distance, usually, 16 inches from the source in long spaced density (LSD) log, while in short spaced density (SSD), it is ± 7 inches, as shown in Fig. 1 (Indonesia 2018).

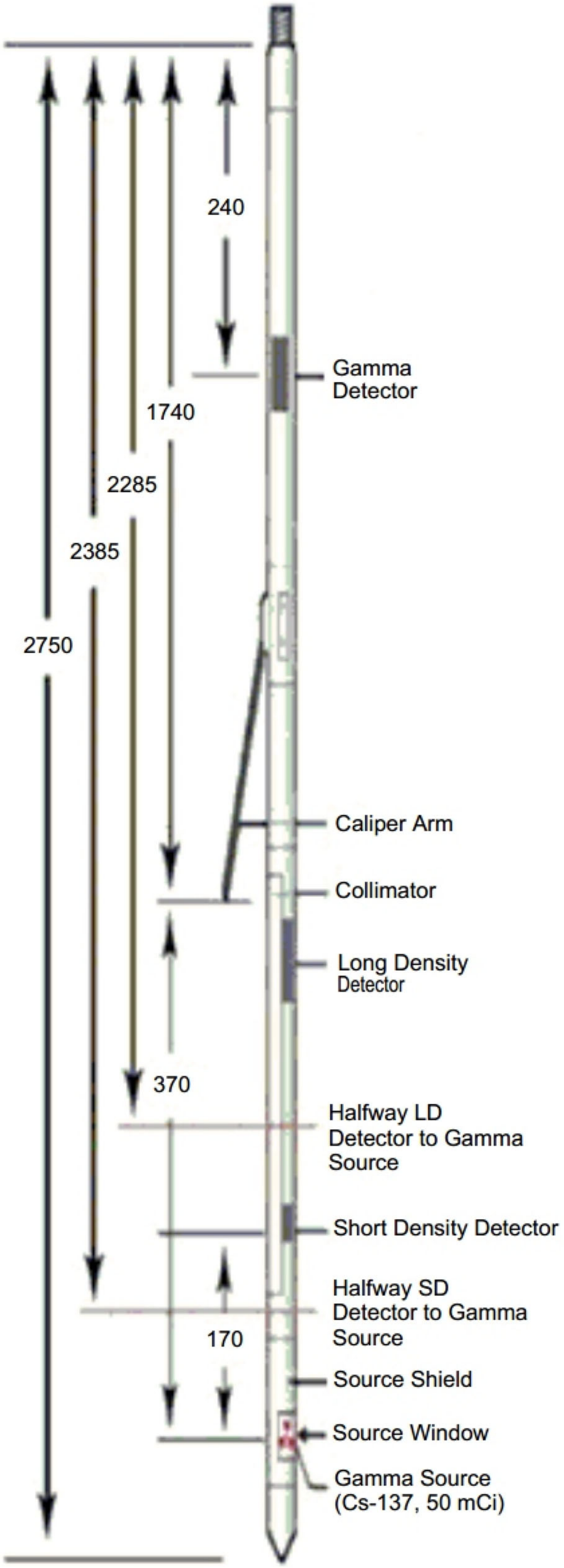
The intensity of gamma-ray reflected depends on the rock density (Darmadi 2015). Meanwhile, when the energy is weak, it implies excessive electrons, grains or minerals per volume are dense. This is also dependent on the rock matrix and pore densities, porosity, borehole diameter, mud cake (mud crust), and source-detector spaces both LSD and SSD. LSD log has an insignificant influence on the borehole wall, which causes it to produce a density value relatively close to the actual one, thereby making it suitable for subsurface evaluation. On the other hand, SSD log has a vertical resolution higher than that of the LSD, therefore it is suitable for measuring subsurface thickness. However, for rocks that do not need high resolution, it is better to use LSD log (Reeves 1971). Several studies have reported that geophysical method is used to test the physical and mechanical properties of rocks with good accuracy (Baibatsha et al. 2019; Hussain et al. 2019). However, the results of this research failed to explain its characteristics. The geophysical method also saves cost in conducting geotechnical investigations with irreplaceable sample needs. Nevertheless, it has not yet achieved good accuracy for interpreting the mechanical properties. (Azahar et al. 2019).

The geophysical methodology accuracy in terms of assessing physical and mechanical properties met the practical requirements. Moreover, it is rapidly determined without cost-effective sampling, thereby resulting in the greatest accomplishment of this research. Based on preliminary studies, the mechanical properties and elasticity are measured by adopting the velocity (sonic log) and density approaches. Empirical analysis of density and gamma-ray is rarely carried out, therefore this research is extremely interesting. The correlation is expected to be determined, thereby enabling the geophysical log data to be of greater use. There have been quite a number of studies like this, but each geological characteristic has a different value. This value needs to be studied in every detailed geological condition. From the results of the previous researchers reviewing, it still cannot be applied in the locations that we examine. The location that we researched, it is quite interesting because this location is a location that has abundant coal resources and reserves. The Warukin Formation is one of the main coal bearing formations in Indonesia, it is as a producer of coal which is shipped worldwide.

2 Materials and methods

This section involves modelling mechanical properties such as cohesion and friction angle, also referred to as the response variables based on geophysical log data, namely long spaced density (LSD), short spaced density (SSD), and gamma-ray, regarded as the predictor variables, obtained from sedimentary rock by carrying out simple linear regression. Laboratory testing was carried out on core samples from drilling activities to obtain cohesion and friction angle data. An unconsolidated undrained triaxial test in accordance with ASTM D2850-87 standard was performed. The drilling activities include ASTM D2113-99 regarding core drilling and sampling of rock site investigation, ASTM D5434-97 regarding field

Fig. 1 Short spaced density (SSD) and long spaced density (LSD)



logging of subsurface exploration, and ASTM D4220-95 regarding preserving and transporting the sample. The rock was described using ASTM D2488-00 standard for soil description and identification (visual manual procedure). This method was selected because the sedimentary rocks and soil in the research location had similar characteristics.

The research is carried out by drilling and geophysical logging of course opens up large costs and it becomes a source of extraordinary research, so whatever the results later can be useful for various purposes or to neglect research. Geophysical logging was carried out after flushing or cleaning the boreholes of mud from drilling activities. Log measurement was performed using GDDC (Gamma Dual Density and Caliper) type probe at a speed of 5 m/min, which is suitable for the characteristics of the research location (Zohra-Hadjadj et al. 2019). The clastic sedimentary rocks consist of sandstones and claystone with poor hardness and deteriorate when exposed (Pazzi et al. 2019). The sandstones are composed of clay-to-sand-sized quartz minerals at a fracture angle of 53° (Supandi 2020; Supandi et al. 2018). Meanwhile, the claystone are composed of clay-sized quartz minerals with clay mineral content of 15% kaolinite and 8% illite (Supandi et al. 2018).

Interestingly, a total of 51 samples acquired from 5 boreholes with various drilling variations were used in this research. The present research ignored the lithology factor, however it put forward the measurement values both from the laboratory and field using geophysical log. The relationship between the response (cohesion and friction angle) and predictor variables (LSD, SSD logs, and gamma-ray) was assumed to have a linear pattern based on the data distribution plot. This was then analyzed using a simple linear regression equation, stated as follows (Supandi 2020)

$$y = a + bx \tag{1}$$

where y and x are the response and predictor variables, a and b are constant, and regression coefficient, respectively. Furthermore, when the model is significant, the proposed framework determines the relationship between x and y. This is also measured by the p-value obtained from F test statistics. The model is then considered significant when the p-value is smaller than the specified significance level at 5%.

3 Results

The LSD values obtained from geophysical log data measurements ranged from approximately 2000–7500 CPS. 80% of the values were within the range of 2000–3500 CPS, 15% were within 4000–5250 CPS, and 5% were relatively within 7000 CPS. The cohesion values ranged from 10 to 100 kPa, with the distribution mostly within 40–100 kPa, and approximately 20% were below 60 kPa. The friction angle values were in the range of 6° to 25° with 80% above 15° and 20% were also below 15°. Visualization of the relationship between LSD and each cohesion and friction angle is shown in Fig. 2. The correlation degree (r) of LSD and cohesion is −0.55 (moderate), while that of friction angle is −0.54 (moderate). The negative sign indicates an inversely proportional relationship, where cohesion and friction angle decreases with an increase in LSD. The models of cohesion and friction angle by LSD, respectively, are as follows:

$$\text{Cohesion} = -\,0.0091\ \text{LSD} + 92.55$$

$$\text{Friction angle} = -\,0.0019\ \text{LSD} + 24.52$$

The predicted error of cohesion ranges from 2.36% to 300.29%, with a mean of 38.74%, while friction angle prediction is within 0.24–92.87%, with a mean of 19.71%.

The SSD (short spaced density) values were approximately within 13,000 to 20,000 CPS. Visualization of the relationship between SSD and cohesion as well as friction angle is shown in Fig. 3. The correlation degree (r) of SSD and cohesion is −0.34 (weak), while that of friction angle is −0.32 (weak). The negative sign indicates an inversely proportional relationship, where cohesion and friction angle decreases as SSD increases. The models of cohesion and friction angle by SSD, respectively, are as follows:

$$\text{Cohesion} = -\,0.0058\ \text{SSD} + 155.09$$

$$\text{Friction angle} = -\,0.0011\ \text{SSD} + 36.59$$

The predicted error of cohesion ranges from 1.09 to 494.62%, with a mean of 50.34%, while friction angle prediction is within 0.25–144.55% with a mean of 23.49%.

The other geophysical log data is gamma-ray, which ranges from approximately 0 to 80 CPS. Visualization of the relationships between gamma-

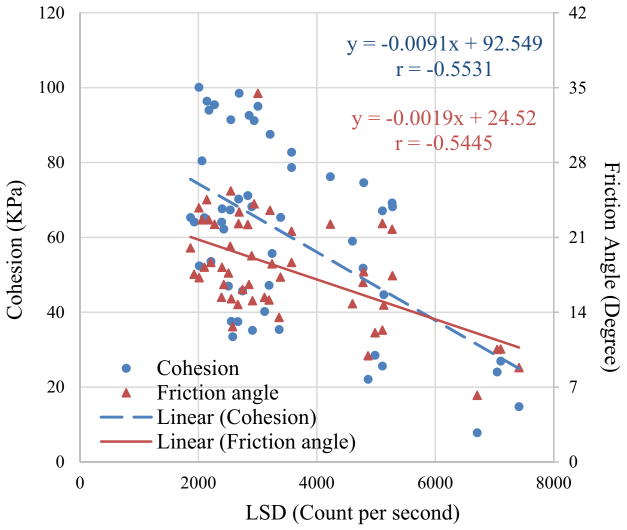


Fig. 2 Relationship plot of LSD (long spaced density) and cohesion as well as friction angle

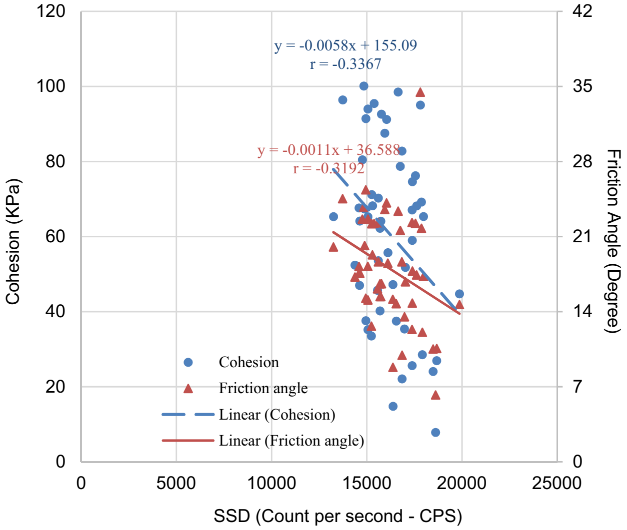


Fig. 3 Relationship plot of SSD (short spaced density) and cohesion as well as friction angle

ray, cohesion, and friction angle is shown in Fig. 4. The correlation degree (r) of gamma-ray and cohesion is 0.04 (negligible), while that of friction angle is − 0.12 (negligible). The models of cohesion and friction angle by gamma-ray, respectively are

$$\text{Cohesion} = -\,0.0589\ \text{Gamma} + 57.08$$

$$\text{Friction angle} = -\,0.0364\ \text{Gamma} + 20.28$$

The predicted error of cohesion ranges from 0.65 to 689.03%, with a mean of 56.14%, while friction angle prediction is within 0.05–177.50% with a mean of 26.05%.

4 Discussion

Table 1 shows the summary of the analysis result, and the prediction of mechanical properties using geophysical log values obtained an error of 19.71% to 56.14%. Based on the p-value of F test statics, the correlation between gamma-ray and mechanical properties was the only relationship that was unable to be determined by the proposed model (p-value ≥ 0.05). Furthermore, a weak correlation exists between the mechanical properties variables (cohesion and friction angle) and geophysical log values (LSD, SSD, and gamma-ray).

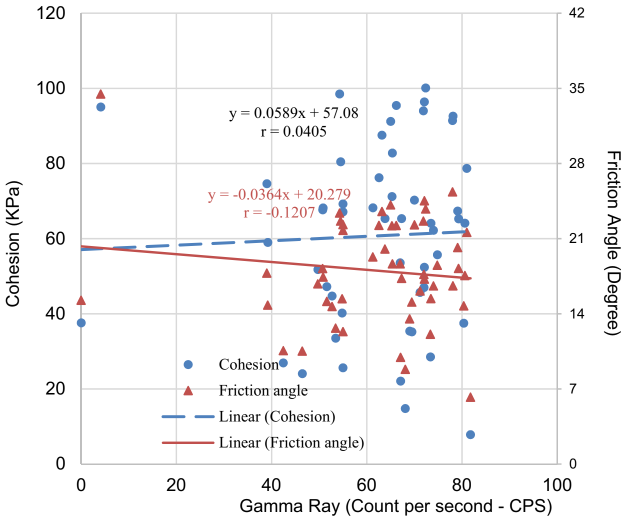


Fig. 4 Relationship plot of gamma-ray and cohesion as well as friction angle

Table 1 Result of model analysis

Model	*p*-value	Error
Cohession = − 0.0091 LSD + 92.55	0.000	38.74%
Friction angle = − 0.0019 LSD + 24.52	0.000	19.71%
Cohession = − 0.0058 SSD + 155.09	0.016	50.34%
Friction angle = − 0.0011 SSD + 36.59	0.022	23.49%
Cohession = 0.0589 Gamma + 57.08	0.778	56.14%
Friction angle = − 0 .0364 Gamma + 20.28	0.399	26.05%

Geological control is one of the reasons a weak correlation was obtained. Certain rock characters were reflected by long-short density values and some gamma rays measured with similar tools and standards. Moreover, clastic sedimentary rocks have a wide space because of the minerals' diverse characters, its composition, and rock cement. According to the clastic sediments, this research was carried out on sedimentary rocks ranging from clay to sand with various mineral compositions. The present research failed to discuss in detail the types of minerals in claystone and is only limited to a literature research. The differences in rock, grain composition, and mineral content are factors that led to an enormous difference between the values of mechanical properties and geophysical logs.

The clastic sedimentary rocks are related to the soil's water content and aquifer type. In accordance with the stratigraphy of the present research, it is possible to find various types of aquifers. Generally, the rocks consist of sandstone and clay, at varying positions, thereby enabling the several aquifer types to be detected, starting from the free, compressed, and semi-stressed ones. This difference in geohydrology control affects sandstone geophysical log readings, while the diverse stratigraphic positions result in varying values. The error is expected to be minimized or develop a strong correlation by clustering around each rock character and geohydrology condition.

The aforementioned geological and geohydrologic conditions control the difference in LSD, SSD, and gamma-ray values. Correlating rock properties with the geophysical log values is realized by clustering each characteristic with its geohydrological condition. This becomes material for a new hypothesis, thereby drawing a correlation in the future. Mechanical properties are also better determined by carrying out laboratory tests with existing standards. Many factors influence geophysical log reading, therefore it is understandable when its value does not strongly correlate with the mechanical property.

Interestingly, continuing the analysis by specifying each rock increases the correlation between the rocks' mechanical properties and the geophysical log measurement results. The clustering of geological conditions causes the rock character and the geophysical log value to be more detailed and accurate. In clastic sediments, fine-grained rocks need to be considered in determining the mineralogy type. The different types of clay minerals and stones influence geophysical log value. The adopted method's results require greater effort, which involves combining data collection to increase the number of samples to obtain a better statistical analysis. This is carried out by representing a rock unit to achieve better accuracy.

From the research results, there is no correlation between material properties, cohesion and friction angle, but from this research, it can be learned that geophysical parameters when data collection must be carried out with consistent parameters, so that data accuracy can be obtained. With consistent parameters, so hypotheses regard the geophysical characteristics, it can be correlated with their material properties, so they can provide many benefits. The hypothesis that each material has its own geophysical character, it is certain, so the research process can be carried out in stages by continuously refining the process. If this process is successful it will be a great novelty that can benefit the mining and other industries. Delivering the research results in accordance with real field conditions is quite important, so even though the research has not yet produced goals, it can improve the process. It is important to be published, so the same research error can be minimized so that in the future it can answer the existing hypothesis.

5 Conclusion

Mechanical properties of fine-grained sedimentary rocks such as claystone and sandstone do not strongly correlate with the values of long spaced density (LSD), short spaced density (SSD), and gamma-ray. The prediction model of these attributes realized by geophysical log data was significantly based on the F test. However, this does not include the gamma-ray, also referred to as the predictor variable. Fortunately, the prediction model realized by LSD obtained an error ranging from 2.36 to 300.29%, with a mean of 38.74% for cohesion and 0.24–92.87% with a mean of 19.71% for friction angle. Conversely, the prediction model by SSD realized an error within the range of 1.09–494.62% with a mean of 50.34% for cohesion and 0.25–144.55% with a mean of 23.49% for friction angle.

Mechanical properties of sedimentary rocks with poor hardness are difficult to predict based on the geophysical log values, especially gamma-ray because numerous factors influence its reading. Therefore, to improve the prediction model, the variables need to be redefined. Determination of mechanical properties is better carried out by performing laboratory testing based on drilling samples. The rock control, mineral composition, and geohydrology conditions are factors that prohibit the correlation between mechanic properties and the geophysical log value. However, continuing this research by detailing each rock character, mineralogy and geohydrology is recommended and tend to become a new hypothesis.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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