Permeability-velocity model for clay bearing and cemented sandstone

Yijie Zhou*, Zakir Hossain
Rock Solid Images Inc, 2600 South Gessner Road, Suite 650, Houston, USA.

Summary

The objective of this study is to experimentally and theoretically revise the relations between porosity, permeability, and elastic wave velocity of diagenetic sandstone. Many such relationships exist in the literature, however, they do not consider diagenetic effects. We found clean sandstone can be modeled with Kozeny’s relation; however it breaks down for clay-bearing sandstones and diagenetically-altered sandstones. Porosity is the first order parameter that affects permeability and elastic properties; clay and cement cause secondary effects on these properties. Combining theoretical models with laboratory measured data, we have derived mathematical relationships for porosity-permeability, porosity-velocity and permeability-velocity in diagenetic sandstone. The effects of clay and cementation are described using coefficients introduced into these relationships. The relationships provided in this study can greatly help to determine permeability and velocity from porosity or to estimate permeability from velocity measurements.

Introduction

Sandstone is one of the most significant groups of reservoir rocks as approximately half of the known hydrocarbon reserves are in sandstone. Sandstones are mainly composed of a mixture of clastic quartz grains. Sandstones have better granular geometry than carbonate rocks, therefore interpretation of their physical properties can be considered to be an easier task. However, sandstones are often found to have undergone diageneric processes. Clay bearing and cemented sandstones are common place in

Figure 1: Geological processes of sandstone diagenesis. (a) Dense packing of quartz grains, (b) Quartz overgrowth cemented sandstone, (d) Pore-filling cemented/clay bearing sandstone.

Figure 2: Cross plot of porosity and permeability for sandstone (Gomez, 2009), clay bearing sandstone (Han, 2010) and cemented sandstone (Hossain et al., 2011). The reference lines represent published porosity-permeability relations. Clay bearing and cemented sandstones show different trends than the traditional models.
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sedimentary basins and can degrade the overall reservoir quality compared to clean sandstones. Diagenesis of sandstones, resulting in for example silica lining (Figure 1b) or pore-filling clay minerals (Figure 1c), can greatly change the shape of inter-granular pores, and the corresponding physical properties. Clay and cement in sandstones also increase the complexity of rock physics analysis.

Porosity and permeability are two of the most important parameters required to characterize the reservoir. Both vary as a function of pore geometry, grain packing, grain shape, pore-filling solids, sorting, and any associated diageneric facies. Kozeny (1927) introduced the relationship between porosity ($\phi$), permeability ($k$) and specific surface area of bulk volume ($S$) using well known Kozeny’s equation as:

$$k = c \frac{\phi^3}{S^2} \quad \text{Equation 1}$$

where, $c$ is Kozeny’s factor. This factor can be estimated from porosity via a simple model of linear 3D interpenetrating tubes (Mortensen et al., 1998):

$$c = \left\{4 \cos \left[\frac{1}{3} \arccos (2\phi - 1) + \frac{4}{3} \pi\right] + 4\right\}^{-1} \quad \text{Equation 2}$$

Figure 2 shows the cross plot of porosity and permeability for clay-bearing sandstone, greensand, and clean sandstone. Different porosity and permeability model curves are also plotted for reference. We can see that some porosity-permeability relations may be captured using reference curves. However, these reference curves do not describe the clay-bearing sandstone and cemented greensand. For clay-bearing sandstone, due to the clay effect, the permeability will decrease, given certain porosities. Similarly, permeability will also decrease due to the cementation in greensand. Diagenesis of sandstone can greatly change the shape of inter-granular pores, the specific surface area of bulk volume will correspondingly change due to the clay and cementation effect, therefore, the traditional Kozeny equation does not apply to such diagenetic sandstone.

The objective of this study is to experimentally and theoretically revisit the relations between porosity, permeability, and elastic wave velocity of diagenetic sandstone. We analyze how porosity relates to permeability, and velocity using laboratory measured and theoretical models. We derive porosity-permeability models for clean sandstone, clay bearing sandstone and glauconite bearing sandstone, which is further combined with rock physics models to derive the permeability-velocity relations for such sandstones.
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Data, Method and Results

We used three laboratory measured data sets: glauconite bearing greensand from the North Sea (Hossain et al., 2011); Fontainbleau sandstone (Gomez, 2009) and clay bearing sandstone (Han, 2010). The glauconite bearing Paleocene greensand is dominated by quartz but weakly cemented to quartz cemented. The mineralogy of Fontainbleau sandstone is 100% quartz with an average grain size of 250 µm. The clay bearing sandstones include 0-30% clay content.

The effects of clay and cement on porosity-permeability relations are complex. Therefore, using the traditional permeability models, we are unable to describe these effects (Figure 2). Figure 3a shows the three models derived for porosity-permeability trends, which are obtained through curve fitting to clean sandstone, clay bearing sandstone and cemented sandstone. Figure 3b shows the model derived porosity-specific surface area of the bulk volume and how this relates to the porosity-permeability trends using Kozeny’s equation. We observe that for each type of sandstone, the porosity and specific surface area of the bulk volume have a linear relationship in the log-log plot. Thus porosity and specific surface area of bulk volume have the following relationship:

\[ \log(S) = a \log(\phi) + b \]  
Equation 3

Combining Equation 3 with the Kozeny’s equation, we have new permeability model:

\[ k = c \phi^{3-2a} \frac{1}{10^{2b}} \]  
Equation 4

where, \( a \) and \( b \) are the coefficients that need to be determined according to different rock types. For clean sandstone, \( a \) is -1.0, and \( b \) is -2.2; for clay-bearing sandstone, \( a \) is -2.5, and \( b \) is -2.3; for greensand with pore-filling cementation, \( a \) is -5.5 and \( b \) is -3.0. \( c \) is Kozeny’s factor, which can be estimated from porosity using Mortensen method (1998). To simplify Mortensen method, we can also derive the relation for porosity-Kozeny’s constant in Figure 3c through curving fitting:

\[ c = 0.15\phi + 0.18 \]  
Equation 5

With the simplified porosity-permeability model provided, assuming we can determine the coefficients \( a \) and \( b \), given certain rock type and porosity, we can easily determine the permeability using by using the modified Kozeny’s equation (Equation 4).

Figure 4 shows velocity and porosity relationships for different sandstones. The samples are plotted together with rock physical modeling as described above. Most of the clean sandstones (yellow points) follow the stiff-sand trend, but the clay-bearing sandstone (black points), and greensands with pore-filling cement (green points) are scattered in different intermediate stiff-sand models due to diagenetic effects.

We simplified the soft-sand and stiff-sand model curves using the curve fitting method. Here, we can see that the soft-sand model usually provides the lower bound of the velocity, and it can be fit with a power equation as:

\[ V_p = 1.86\phi^{0.28} \]  
Equation 6

And stiff-sand model provides the upper bound of the velocity, and it can be fitted with a linear equation as:

\[ V_p = -8.23\phi + 6.04 \]  
Equation 7

With the above two equations, we can simplify the estimation of the bounds of the velocity, given certain porosity. However, the coefficients within the equations may change respectively with different rocks.
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Combining Equation 4, 6, 7, we can derive the permeability-velocity relations for different diagene tic sandstones, which are shown in Figure 5. For the first and second cases modeled with the stiff-sand model, we have:

\[
k = c \left( \frac{6.04 - V_p(\phi)}{8.23} \right)^{3-2a} 10^{-2b} \quad \text{Equation 8}
\]

The coefficient should change according to different sandstones. For the third and fourth cases modeled with soft-sand model, we have:

\[
k = c \left( \frac{V_p(\phi)}{1.86} \right)^{0.28(3-2a)} 10^{-2b} \quad \text{Equation 9}
\]

Conclusions

The permeability for clean sandstone can be estimated with Kozeny’s relation; however it breaks down for clay-bearing sandstones and diagenetically-altered sandstones. We propose new correlation models for specific surface area of bulk volume, which can consider diagenetic effects by changing the coefficients of the correlation. The new correlation, combined with Kozeny’s relation can better predict the permeability of different sandstones, including clay-bearing sandstones and diagenetically-altered sandstones. For porosity-velocity relations we employed simplified soft-sand and stiff-sand models. Combining these relations with the new permeability models, we defined permeability-velocity relations for clay-bearing sandstones and diagenetically-altered sandstones.
EDITED REFERENCES
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REFERENCES


