Effect of Compaction History on Pore Pressure Prediction

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Summary

Correct pore pressure prediction relies on the recognition of formation compaction history and good characterization of the velocity pressure relationships under various scenarios. Experiments were attempted to better characterize the normal compaction trend and unloading curves. Theoretical models were used to better understand the pore pressure's effect on velocity.

Introduction

The relationship between velocity and pressure is currently the main resource used to predict pore pressure in formation. Eaton's (Eaton 1975) equation remains the most popularly used method in the industry. While the overburden pressure follows a stable trend, the pore pressure experiences more variation during compaction. Furthermore, the effect of the pore pressure on velocity and other rock properties does not follow a one to one relationship. Figure 1 schematically depicts the pressure paths for three different scenarios. For a normal compaction trend, the overburden and pore pressures increase at approximately a 2:1 ratio during subsidence. If undercompaction occurs, the overburden and pore pressures may increase at approximately the same rate (dashed dotted line). In the third scenario, the formation first went through normal compaction, and then underwent a pore pressure increase which would most possibly be caused by the fluid expansion. Although the final overburden/pore pressure pair can reach the same value from scenario 2 and 3, the formation rocks have different compaction levels thus exhibit different properties including velocity, resistivity, and porosity. This non-uniqueness in velocity-pressure relationships imposes ambiguity into the pore pressure prediction.

To reduce the ambiguity and improve the pore pressure prediction, we need attempts in the following four aspects:

1. Better understanding on the pore pressure mechanism and its relationship to velocity.
2. Ways to recognize the compaction history of the formation: mostly by geologic interpretation, maybe with help from multi-parameter analysis as suggested by Bowers.
3. Better characterization on the normal compaction trend by experiments, for different lithology, and different geologic settings.
4. Also to characterize the unloading trend by experiments.

In this report, we present our recent work mainly on points 1, 3, and 4.

Pore pressure mechanism

An observation on North Sea shale showed the velocity change more likely follows the confining pressure change but not the differential pressure change (Yao et al., 2007). In other words, the velocity is less affected by the pore pressure change. (Figure 2)

This raised the question on the sensitivity of velocity on pore pressure change and imposes a challenge to the current pore pressure prediction methods, which are based on the velocity-Pd correlation.

The elastic properties of porous media are mainly controlled by the contact status. The hydrostatic confining pressure and the pore fluid pressure work differently to change the status of the contacts. Wyllie experimentally demonstrate that velocity depended on the differential pressure defined as (Wyllie 1958).

$$P_d = P_c - P_p \quad (1)$$

But Brandt (1955) indicated the velocity should depends on an effective pressure defined as

$$P_d = P_c - nP_p \quad (2)$$

It suggests the pore pressure effect on velocity needs be adjusted by a coefficient n, which is normally less than 1. Further works by Christensen and Wang (1985), and Hornby (1996) revealed that n can be either greater or less than 1, depending on the lithology, compaction level, and wave propagation mode.

To better understand why the n value changes with the compaction level, a pseudo 1D contact model is used in Figure 3. Assuming the total length 1, the pore and contact have the length of ϕ and 1-ϕ respectively. A hydrostatic confining pressure P_c is applied on the total length from outside and a pore pressure P_p is applied from the pore inside. We want to calculate the pressure P_{ct} exerted on the contacts. The force balance requires

$$P_c = P_{ct} \cdot (1-\phi) + P_p \cdot \phi \quad (3)$$

So we can solve the P_{ct}:

$$P_{ct} = \frac{1}{(1-\phi)} \cdot P_c - \frac{\phi}{(1-\phi)} \cdot P_p \quad (4)$$

This solution suggests that not only does the pore pressure have a reduced influence on contact properties, but also that the confining pressure has an enhanced influence on contact properties.

Furthermore, by modifying the Hertz-Mindlin model to include the pore pressure, we can also obtain the force between any two contacts:

$$F = \frac{4\pi R^2}{C(1-\phi)} \cdot P_c - \frac{4\pi R^2 \phi}{C(1-\phi)} \cdot P_p \qquad (5)$$

It has the very similar pattern as (4).

The above analysis only simply takes into account the difference of the area that can bear the pore pressure and confining pressure. It just visualizes part of the micro mechanism controlling the pressure effect on velocity.

Compaction experiments

1. Silt Compaction

In order to simulate the compaction process, a special sample hold was designed to hold the loose granular material. Both axial and radial stress can be controlled. P and S wave velocities can be measured by ultrasonic transducers attached to both end of the sample. In the meantime, the resistivity of the sample can be measured simultaneously by comparing the voltage on the sample and a standard reference resistor. The sample porosity change can be monitored by the injected or ejected pore fluid. Figure 4a and Figure 4b are the schematic drawings of experiment setup and resistivity measurement circuit.

A silt sample was measured to study the shallow compact trend of velocity, porosity, and resistivity. The grain density used in this experiment was measured 2.62g/cc by a porosimeter. By calculating the bulk volume and sample weight, we estimated the initial porosity at the beginning of compaction to be 56%. This porosity was reduced to 48% by applying 300psi axial stress only for 3 days. After that, the sample was saturated with 20,000ppm brine using 100psi pore pressure. By recording the injected brine, we found the porosity quickly reduced to 40%. The pore fluid lubricated the grain contacts and helped the re-arrangement of the grains, thus significantly reducing the porosity.

Keeping the pore pressure constantly at 100psi, we increased the confining pressure by 200psi at each step, until reaching 1900psi. At each step the P and S wave velocities, porosity, and resistivity were measured 3 times to ensure the system equilibrated before going onto the next pressure. This uploading curve took 14 days to finish. After that, we keep the confining pressure constant at 1900psi, and increased the pore pressure by 200psi at each step until reaching 1700psi, to obtain an unloading curve.

Figure 5 shows the results of velocity, resistivity, porosity, sample length, and formation factor vs. differential pressure, along with a crossplot of Vp vs. resistivity. From these plots, we observed in all cases, the unloading curves substantially deviate from the loading curves. The compaction process is mainly an inelastic process. But the release of the stress can only recover the elastic deformation not the inelastic deformation. Bowers (2002) suggested the concepts of bulk properties and transport properties. Density, porosity, and sample length belong to bulk properties and undergo less rebound when stress is released. But velocity and resistivity belong to transport properties, and undergo more elastic rebound during unloading curve. In our experiment, we compared the rebound on P wave velocity, porosity, and sample length (Figure 6), and found that the P wave velocity has largest rebound, second to the porosity, and the sample length has the least rebound. This observation complies with Bowers' suggestion. If the well logs are available, this principle provides an effective way to assess the occurrence and level of unloading, which in turn indicates the overpressure associated with fluid expansion. However, this requires more experiment data to provide the quantitative guideline.

2. Different compaction paths on tight gas sandstone

In this experiment, we want to test how different compaction paths can change the contact status, and how the differences on contact status can change the relationship between velocity and pressure.

A tight gas sandstone sample with a porosity of 4.8% was used in this test. This core sample has undergone many pressure cycles before this test; therefore we assumed no grain re-arrangement and no large inelastic deformation will happen in this test. Only small changes on contact area were expected.

After the sample was saturated with 20,000ppm brine under Pc=2MPa, Pp=1MPa, we managed to increase the Pp, Pc parallel until the Pp reached 5MPa, then slowly increase the Pc to 15MPa. The P wave velocity and resistivity were measured after equilibrium. Then we reduced the pore pressure to 0.2MPa and kept it for 3 hours before increased it back to 5MPa. Velocity and resistivity were measured again. The results are plotted in Figure 7 and Figure 8. The pressure conditions of the two measurements are exactly the same. But the release of the pore pressure allows the rock to have further compaction and changes the contact status. After this change, the rock is no long the same rock as previous, so even the pore pressure was restored to its original value, it now acts on a different system, and thus have different influence on the properties of this new system. The same procedures were repeated at increased confining pressure of 20MPa, 25MPa, and 30MPa. The same results were observed on both velocity and resistivity.

The above experiments are part of the initial attempts to characterize the compaction trend and unloading trend. To provide practical guidelines to pore pressure prediction, more experiment measurements are demanded to systematically collect data on different lithology from different geology settings. We also expect such experiments may help to reveal more about the micro mechanism controlling the pressure-velocity relationship.

Conclusion

Compaction history has significant impact on the velocity pressure relationship for formation rock. Laboratory simulated silt compaction was done to study the compaction and unloading trend. A 1D model and modified Hertz-Mindlin model were used to analyze the micro-mechanism to better understand how pore pressure affects the acoustic/elastic properties under different contact status. The behavior was verified by the experiment on a tight gas sandstone sample. More lab work is needed to characterize velocity-pressure trend for different compaction history. Including other attributes like resistivity, porosity, and density may help to reveal compaction history, and improve pore pressure prediction.

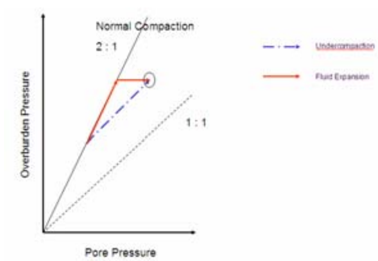

Figure 1. Pressure paths for three different compaction history scenarios.

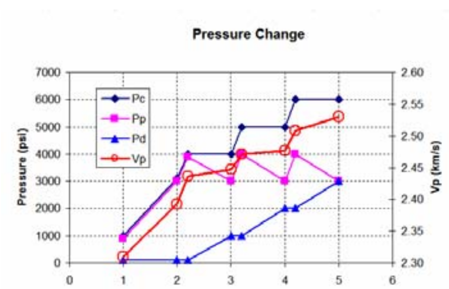

Figure 2. Velocity measurements on a North Sea shale show the velocity is more sensitive to confining pressure change and less sensitive to pore pressure change (Yao, 2007).

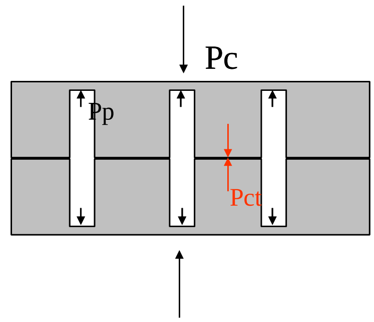

Figure 3. A pseudo 1D model to show enhanced confining pressure effect and reduced pore pressure effect on contact status.

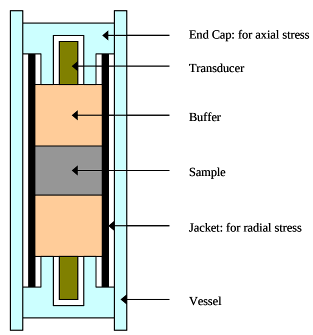

Figure 4a. Schematic setup for compact experiment.

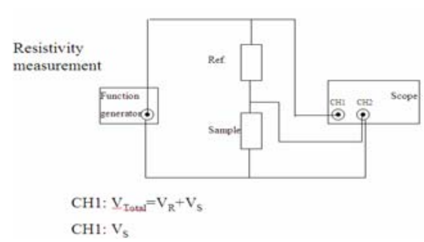

Figure 4b. Circuit for resistivity measurement in compaction experiment.

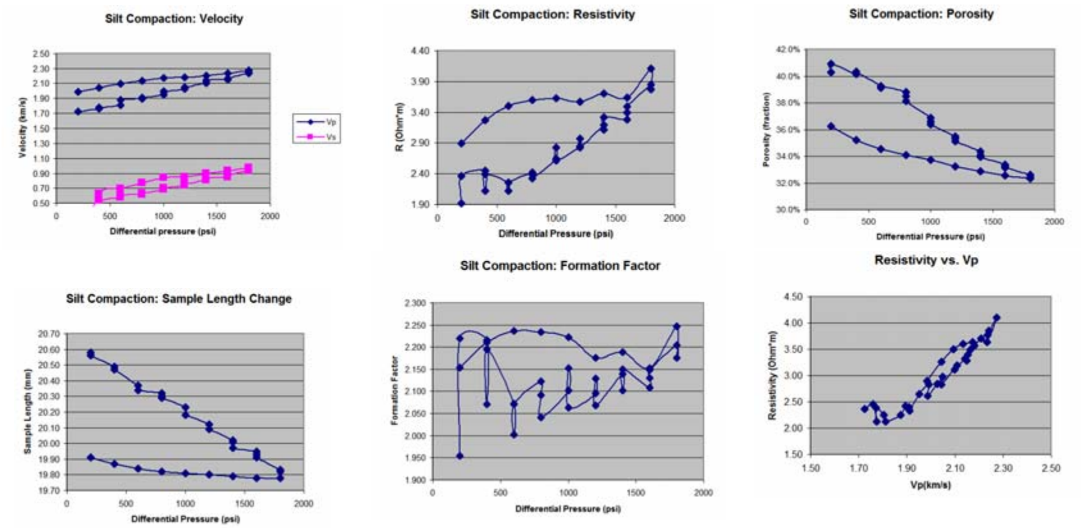

Figure 5. Silt compaction and unloading trends for velocity, resistivity, porosity, sample length, and formation factor. The bottom right is a crossplot of Vp vs. resistivity.

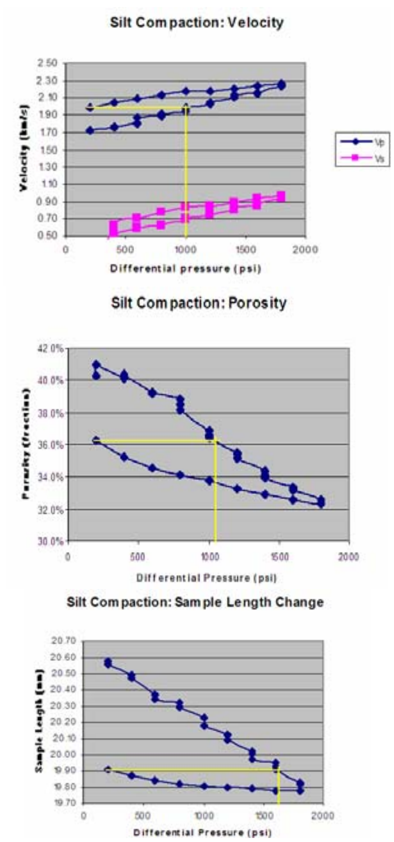

Figure 6. On unloading process, P wave velocity has largest rebound, second to the porosity, and the sample length has the least rebound.

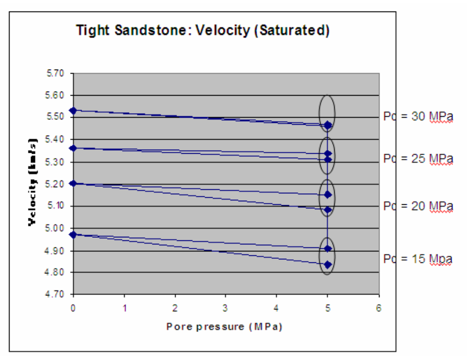

Figure 7. Different pressure paths change the contact status, and velocity-pressure relationship.

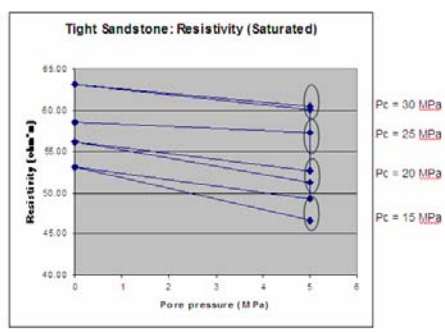

Figure 8. Different pressure paths change the contact status, and velocity-resistivity relationship.

EDITED REFERENCES

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