

Comparison of dynamic and static bulk moduli of reservoir rocks

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Summary

In traditional ultrasonic measurement on reservoir rocks to study the stress and saturation effects on seismic velocities, the pressure dependent pore compressibility can be measured at the same time. From pore compressibility measurement, the static pore stiffness and bulk modulus can be determined. Previous studies on the relation between dynamic and static moduli are often based on the tri-axial testing of dry samples. The tri-axial testing may introduced stress induced anisotropy effect that interfere study of the relation between the dynamic and static moduli. Based on traditional ultrasonic measurement under hydrostatic stress, relation between dynamic and static bulk modulus is investigated. The pore stiffness primarily controls the relation between the static to dynamic bulk modulus. For sandstone, when the pore stiffness is greater than 6 GPa, the dynamic bulk modulus is approximately equal to the static bulk modulus. Under in-situ conditions when the rocks are fully saturated and under substantial stress load, the differences between the static and dynamic properties may be not important. Therefore, dynamic properties derived from seismic data may be directly applied on geomechanics.

Introduction

The tectonic deformation of the earth crust is determined by the static elastic properties of the rocks. The static properties are also important for predicting in-situ stress, reducing drilling risk and enhancing reservoir productivity in the petroleum industry. The static properties of the subsurface rocks can usually not be measured in situ. The static measurement of rocks are usually much more expensive than the dynamic property measurement. While the dynamic elastic properties of the subsurface rocks, even the inner core of the earth, can be inferred from seismic data. Therefore, it is important to know the differences between the dynamic and static properties. It is important to infer the static properties from the dynamic properties.

Several studies have tried to investigate the relationship between the static and dynamic properties (Cheng, 1981; van Heerden, 1987; Christaras and Mosse, 1994; Najibi, et. al, 2015). For static measurements, strain gauges are usually applied to measure the strains in vertical or transverse directions of a cylindrical sample. The measurement can very likely be affected by the

manufacturing quality of the strain gauge, the way strain gauge is applied to the testing sample and experiences of the testing conductor. The uneven lengths of the testing sample and difference in elastic properties between the testing sample and end caps may cause heterogeneous deformation of samples. The above factors may introduce significant uncertainty in the static measurement results. In most of the studies, the implicit assumption of the static and dynamic measurements is that the testing sample is isotropic in elastic properties. When the tri-axial measurement system is utilized for studying the relationship between the static and dynamic properties, stress induced anisotropy may be a major contributor to the difference between static and dynamic elasticity and is dominant for rocks with high crack density (Blake and Faulkner, 2016).

In this study, we will introduce a new methodology to study the relationship between dynamic and static bulk moduli of porous rocks under hydrostatic stress.

Experiment set up and procedures

No instrument are specially designed to conduct this study. For regular pressure dependent velocity measurement on porous rocks, both dynamic process and static process are involved in the measurement procedure. Propagation of the

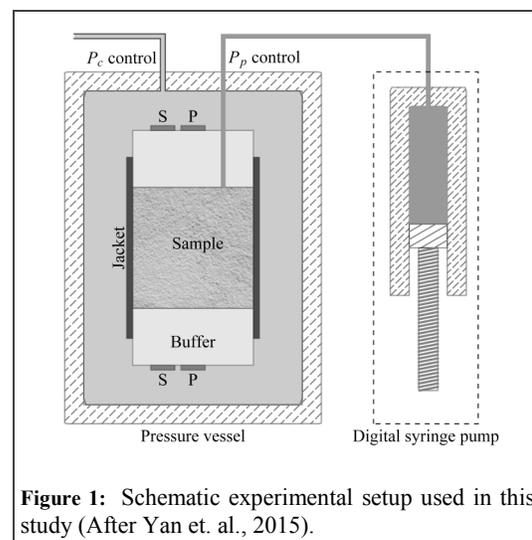


Figure 1: Schematic experimental setup used in this study (After Yan et. al., 2015).

Static and Dynamic Bulk Moduli

ultrasonic waves is a dynamic process; the deformation of the testing sample between different pressure conditions is a static process. The measurements were done by Han (1986).

Figure 1 shows the diagram of pressure dependent ultrasonic velocity and porosity measurement. Both the confining pressure (P_c) and the pore pressure (P_p) are controlled by the digital pumps. The confining pressure simulates the stress produced by the overburden rocks. The pore fluid and the confining fluid are separated by the buffers and the jacket which holds the cylindrical core sample. During the measurement, the pore pressure is set to a desired value and then kept constant so that effect of pore fluid compressibility can be ignored. With variation of the confining pressure, the pore fluid will be absorbed into or squeezed out from the pore system, and the amount of the pore fluid volume variation can be read from the digital pump. Therefore, we can measure the velocities and pore volume changes with differential pressure (the difference between P_c and P_p) simultaneously. There is a difference between differential pressure and effective pressure, and the elastic properties of porous media are affected by the effective pressure. If the confining pressure is much higher than the pore pressure, which is our case, the difference between effective pressure and differential pressure is usually not important.

To estimate the pore compressibility, we still need the traditional porosity measurement, which is often conducted at zero effective pressure using helium porosimeter. The primary uncertainty in monitoring pore volume change comes from the coupling between the core sample, the buffers and the jacket. An expedient handling is to assume that the porosity measured by the helium porosimeter equals to the porosity when the sample is properly coupled with its surroundings (buffers and jacket), usually under differential pressure around 5 MPa. With decreasing confining pressure, the pore volume increases and more fluids will be absorbed into the pore system from the reservoir tank of the digital pump. For a typical 1–1/2 inch reservoir core sample, the total pore volume change for differential pressure variation range of 5–50 MPa is around 0.1–0.5 ml. The volume of the reservoir tank of the digital pump is monitored and displayed in real time, with a resolution that can be as high as 2.5 nanoliters depending on the digital pump model. At each pressure measurement point, the waiting time for the pore fluid system to reach pressure equilibrium is 30 minutes. This way, the measured pressure dependent porosity can be reasonably reliable.

Measurement results

The pressure dependent velocity measurement are conducted on 70 samples at confining pressures of 5, 10, 20, 30, 40 and 50 MPa at both room dry and fully water saturated

conditions. The measurements are done at stress downloading cycle. The pore pressure are kept at 1 MPa for measurements at saturated condition. Using Berea 5-600, Figure 2 shows pressure dependent dynamic ultrasonic velocities and static porosity changes.

Estimation of pore stiffness and static dry bulk modulus

The pore compressibility or stiffness can be directly estimated from the measured pore volume change using equation

$$c_\phi = \frac{1}{K_\phi} = -\frac{1}{v_p} \frac{\partial v_p}{\partial P_c} \Big|_{P_p} = -\frac{1}{\phi} \frac{\partial \phi}{\partial P_c} \Big|_{P_p} \quad (1)$$

Figure 2 shows the pressure dependent pore stiffness for Berea 5-600 using the gradient of the fitting curve of the measured pore volume change. The pore stiffness can also be directly derived from pore volume change between the

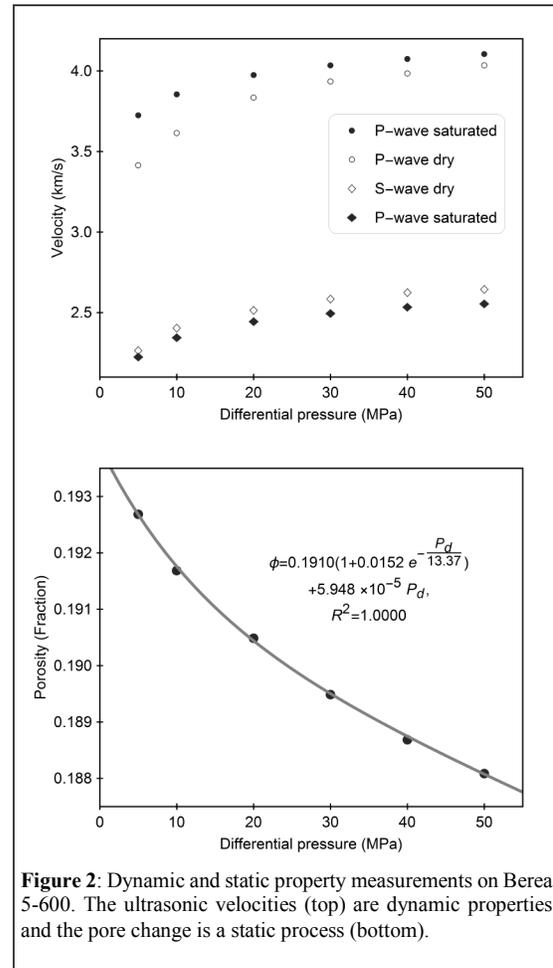


Figure 2: Dynamic and static property measurements on Berea 5-600. The ultrasonic velocities (top) are dynamic properties and the pore change is a static process (bottom).

Static and Dynamic Bulk Moduli

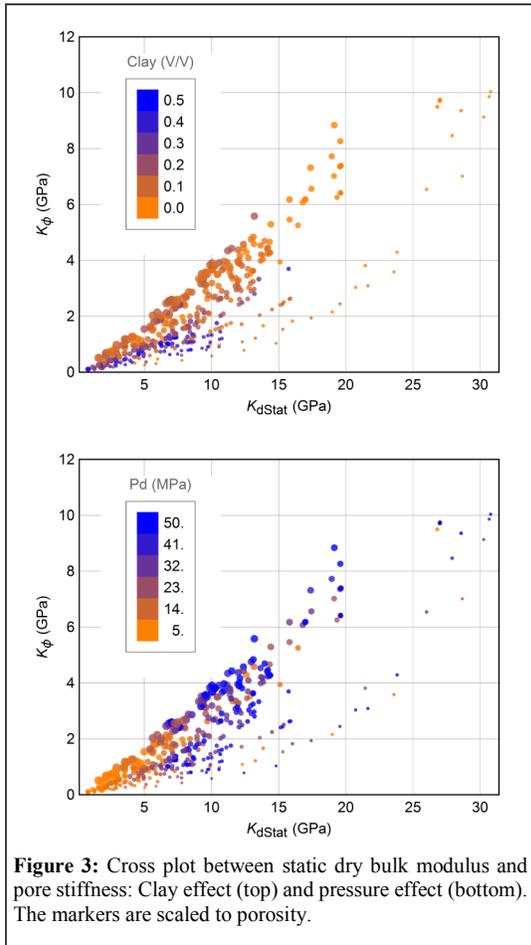


Figure 3: Cross plot between static dry bulk modulus and pore stiffness: Clay effect (top) and pressure effect (bottom). The markers are scaled to porosity.

pressures measuring points. We use stiffness estimated from the fitting curve because it removes part of measurement uncertainty.

The static dry bulk modulus can be determined from (Brown and Korringa, 1975; Mavko et al., 1998)

$$\frac{1}{K_d} = \frac{1}{K_m} + \frac{\phi}{K_\phi} \quad (2)$$

Fig. 3 shows the cross plots between dry static bulk modulus and pore stiffness, using color scales of clay content and different pressure respectively. The data point size is scaled to porosity. It can be seen that pore stiffness generally increases with static bulk modulus. For the same static bulk modulus, higher clay content usually has lower pore stiffness. Most of the rocks have low pore stiffnesses less than 1 GPa when the pressure is low. Lower porosity does not necessarily correspond to greater pore stiffness.

Comparison of dynamic and static dry bulk moduli

The dynamic bulk modulus is estimated from the ultrasonic velocities using

$$G_{dDyn} = \rho V_{sd}^2, \quad (3)$$

$$K_{dDyn} = \rho V_{pd}^2 - \frac{4}{3}G_{dDyn}. \quad (4)$$

Fig. 4 shows the pressure effect on the relationship between the dynamic and static bulk modulus of Berea 5-600 under dry conditions. With increasing of the differential pressure, the difference between the dynamic bulk modulus and static bulk modulus decreases.

Figure 5 shows the relation between pore stiffness and the ratio of static to dynamic dry bulk modulus for all the

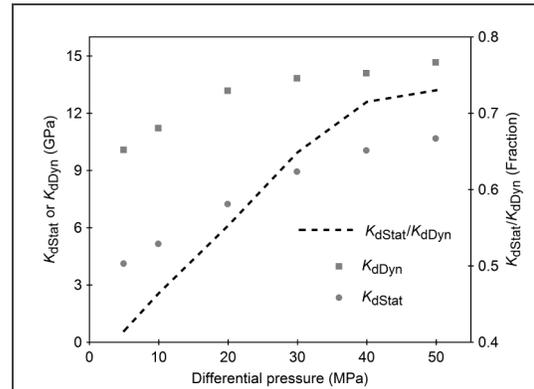


Figure 4: Effect of pressure on relationship between dynamic and static dry bulk modulus for Berea 5-600.

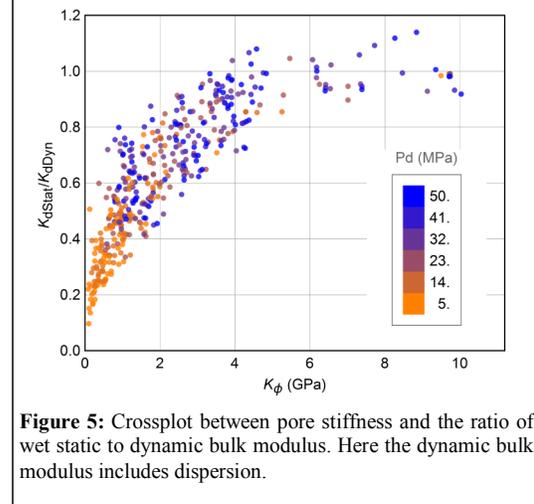


Figure 5: Crossplot between pore stiffness and the ratio of wet static to dynamic bulk modulus. Here the dynamic bulk modulus includes dispersion.

Static and Dynamic Bulk Moduli

samples. The ratio changes rapidly when the pore stiffness is in range of 0-4 GPa. Above pore stiffness of 6 GPa, the ratio is basically kept at 1.0. When the static to dynamic bulk modulus ratio is below 0.4, the differential pressure is usually low. At low pressure, the velocity dependence of pressure observed in laboratory testing is primarily caused to open cracks, which may be the primary factor causing the low ratio of the static to dynamic bulk moduli.

Comparison of dynamic and static wet bulk moduli

The dynamic wet bulk modulus is estimated from the ultrasonic velocities using

$$G_{satDyn} = \rho_{sat} V_{ssat}^2, \quad (5)$$

$$K_{satDyn} = \rho_{sat} V_{psat}^2 - \frac{4}{3} G_{satDyn}. \quad (6)$$

The static wet bulk modulus can be calculated from the Gassmann equation

$$\frac{K_{sat}}{K_m - K_{sat}} = \frac{K_d}{K_m - K_d} + \frac{K_f}{\phi(K_m - K_f)}. \quad (7)$$

In Gassmann equation, assuming the mineral and fluid bulk moduli do not depend on static or dynamic measurement, the predicted K_{sat} is a static property if the input dry bulk modulus is static; it is a dynamic property if the input dry bulk modulus is a dynamic property.

Figure 6 shows the relation between pore stiffness and the ratio of wet static to dynamic bulk modulus for all the samples. Here the wet bulk modulus is calculated using equation (5) and (6). Compared the Figure 5, the difference between the static bulk modulus and dynamic bulk modulus is not as evident at low pore stiffnesses as the case when the rocks is dry. With increasing of pore stiffness, the ratio closes to a value around 0.9. The ultrasonic velocities measured at saturated conditions may include significant dispersion effect (Yan et. al, 2014, Yan et. al 2016). The dispersion effect may be less significant in seismic data. Therefore, it might be more rational to use the dynamic bulk modulus predicted by Gassmann equation. As shown in Figure 7, when the dynamic bulk modulus at low frequency limit is used, the difference between static and dynamic bulk modulus becomes further less pronounced. When the pore stiffness is above 6 GPa, the ratio generally stays at 1.0. Which means that at the subsurface below a certain depth, the static elastic properties can be represented by the dynamic properties.

Conclusions

A new methodology for studying the relation between the static and dynamic elastic properties of porous rocks is

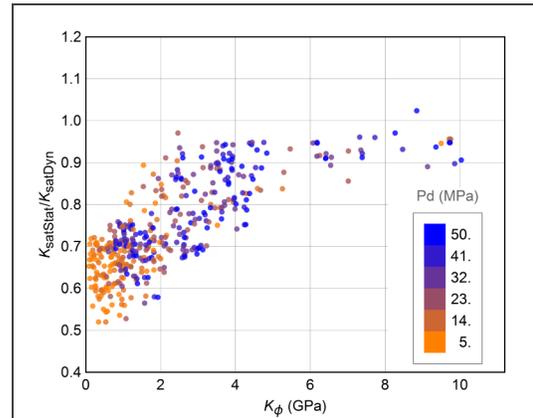


Figure 6: Crossplot between pore stiffness and the ratio of wet static to dynamic bulk modulus. Here the dynamic bulk modulus is calculated using ultrasonic velocities measured on fully saturated rock and it includes dispersion.

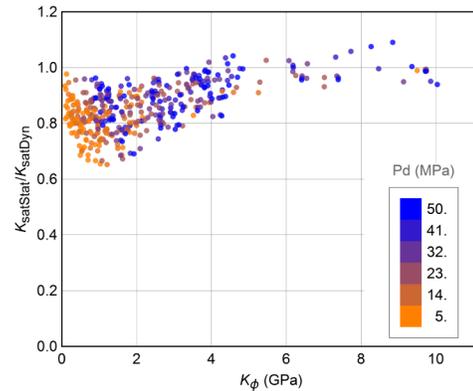


Figure 7: Crossplot between pore stiffness and the ratio of wet static to dynamic bulk modulus. Here the dynamic bulk modulus is calculated using the Gassmann equation and does not include dispersion

brought up. It is applicable and cost efficient. The pore stiffness, significantly affected by cracks, primarily controls the relation between the static to dynamic bulk modulus. Under the in-situ conditions when the rocks are fully saturated and under substantial stress load, the differences between the static and dynamic properties should be insignificant. Therefore, dynamic elastic properties derived from seismic data may be directly used for geomechanical applications.

Acknowledgement

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

- Blake, O. O., and D. R. Faulkner, 2016, The effect of fracture density and stress state on the static and dynamic bulk moduli of Westerly granite: *Journal of Geophysical Research Solid Earth*, **121**, 2382–2399, <http://doi.org/10.1002/2015JB012310>.
- Brown, R. J. S., and J. Korrinda, 1975, On the dependence of the elastic properties of a porous rock on the compressibility of the pore fluid: *Geophysics*, **40**, 608–616, <https://doi.org/10.1190/1.1440551>.
- Cheng, C. H., 1981, Dynamic and static moduli: *Geophysical Research Letters*, **8**, 39–42, <https://doi.org/10.1029/GL008i001p00039>.
- Christaras, B., F. Auger, and E. Mosse, 1994, Determination of the moduli of elasticity of rocks, comparison of the ultrasonic velocity and mechanical resonance frequency methods with direct static methods: *Materials and Structures*, **27**, 222–228, <https://doi.org/10.1007/BF02473036>.
- Han, D.-H., 1986, Effects of porosity and clay content on acoustic properties of sandstones and consolidated sediments: Ph.D. thesis, Stanford University.
- Mavko, G., T. Mukerji, and J. Dvorkin, 1998, *The rock physics handbook*: Cambridge University Press.
- Najibi, A. R., M. Ghafoori, G. R. Lashkaripour, and M. R. Asef, 2015, Empirical relations between strength and static dynamic elastic properties of Asmari and Sarvak limestones, two main oil reservoirs in Iran: *Journal of Petroleum Science and Engineering*, **126**, 78–82, <https://doi.org/10.1016/j.petrol.2014.12.010>.
- van Heerden, W. L., 1987, General relations between static and dynamic moduli of rocks: *Int. J. Rock Mechn. Min. Sci. & Geomech. Abstr.*, **24**, 381–385, [https://doi.org/10.1016/0148-9062\(87\)92262-5](https://doi.org/10.1016/0148-9062(87)92262-5).
- Yan, F., D.-H. Han, 2016, Effect of pore geometry on Gassmann fluid substitution: *Geophysical Prospecting*, **64**, 1575–1587, <https://doi.org/10.1111/1365-2478.12348>.
- Yan, F., D.-H. Han, and X.-L. Chen, 2015, Pore aspect ratio spectrum inversion from ultrasonic measurements and its application: *Journal of Computational Acoustics*, **23**, 1540009, <https://doi.org/10.1142/S0218396X15400093>.
- Yan, F., D.-H. Han, Q. Yao and L. Zhao, 2014, Prediction of seismic wave dispersion and attenuation from ultrasonic velocity measurements: *Geophysics*, **79**, no. 5, P1–P8, <https://doi.org/10.1190/geo2013-0416.1>.