DEPENDENCE OF ULTRASONIC VELOCITIES AND DYNAMIC ELASTIC ROCK PROPERTIES ON STRESS AND SATURATION CHANGES

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ABSTRACT
Ultrasonic velocity measurement tests were conducted on 45 sandstone samples having a range of porosity and permeability from a Middle Eastern oil field to assess the effect of stress and saturation changes on the velocity values and the associated dynamic moduli. The analysis of the experimental data suggests that the change in above-mentioned rock properties is caused by both stress and saturation levels in varying degree depending on the porosity. The velocity values showed an increase from 10% to 80% when the effective stress was increased from 500 psi to the reservoir stress value. Velocity increase was observed to be significant for high porosity samples with respect to change in stress. Moreover, samples under dry state showed much more stress-dependent velocity increase compared to the values under fully saturated and at irreducible water saturation (Swi). Further, stress increment under dry condition, affects both the shear wave velocity (Vs) and the compressional velocity (Vp) almost in the same range. However, under saturated and at Swi conditions, Vs shows significant stress dependent increase compared to Vp. Furthermore, Young's modulus and shear modulus are considerably sensitive to stress variation compared to saturation whereas bulk modulus shows significant change with saturation and is relatively unaffected by stress increase except under dry condition.

INTRODUCTION
The stress and saturation changes occur around the wellbore as well as at the reservoir and basin scale due to drilling and production operations. These changes can significantly alter petrophysical properties including porosity, permeability, compressibility and wave velocities [1, 2]. For instance, 4-D seismic technique for studying the response of reservoir with time is governed by the combined effect of saturation and the associated stress change due to production activities.

The acoustic wave velocities measured on core samples are important parameters for developing and studying correlations between seismic velocities and other reservoir properties such as porosity, permeability, mineralogy, fluid type, and saturation levels. In addition, they are also routinely used to derive dynamic elastic properties and establish their relationship with the static values for rock mechanics applications [3-5]. The velocity measurements, preferably, should be made under simulated downhole conditions at least to the extent of stress and saturation. However, due to time limitations and financial constraints, they are frequently measured under minimal pressure and without saturating the rock samples to their in-situ value [6]. The behavior of dynamic rock moduli under varying stress and saturation could be different compared to the velocity values as the former depend both on the velocity and other rock properties such as density. The mathematical form of these moduli can be found in [7].

The objective of the paper is to study the combined effect of stress and saturation changes on the ultrasonic velocities and dynamic rock moduli of sandstone cores having a range of porosity and permeability collected from a Middle Eastern oil field.

EXPERIMENTAL PROCEDURE

The ultrasonic velocity measurements include one compressional velocity (Vp) along the length of the sample and two orthogonal shear wave velocities (V_{S1} & V_{S2}) normal to the length of the sample. For the present study, only the average value of V_{S1} and V_{S2} represented by Vs has been reported. Majority of the samples were having porosity less than 17%; only a few had porosity in the range of 20-30%. The measurements were made using two distinct hydrostatic effective confining pressures of 500 psi and the net reservoir pressure which was either 3500 spi or 5000 psi depending on the depth of the reservoir. The effective reservoir pressure was calculated using the procedure adopted from Worthington et al [8]. The measurements were conducted for dry, fully brine saturated, and at Swi conditions under ambient temperature with pore pressure maintained at atmospheric. The Swi value of samples was attained by displacing pore fluid with Nitrogen using the standard porous plate method.

DISCUSSION OF RESULTS

The following sections describe the results of present study focused on the effect of stress and saturation changes on ultrasonic velocities and dynamic rock moduli of sandstone cores.

Effect of Confining Pressure and Saturation on Ultrasonic Velocities

The percentage increase in velocity when pressure was increased from 500 psi to the reservoir stress value is shown in Figures 1-a and 1-b as a function of porosity of rock samples. Figures 1-a, and 1-b show that stress induced increase in velocity becomes greater as the porosity of the sample becomes larger. Moreover, samples under dry state showed much more stress-dependent velocity increase compared to the values under fully saturated and at Swi. This velocity increase was observed to be up to 80% for both Vp and V`s. However, under dry condition, the effect of stress is almost identical for both Vp and Vs. This can be more clearly seen in Figure 1-c where data lies almost near to Y=X line for dry condition with Vp being slightly more affected by stress than Vs.

When the rock is saturated, the liquid in pores in addition to the rock skeleton, serves as a traveling medium for Vp resulting in velocity increase compared to that at dry condition.

However, Vs is not affected by the fluid in the pores. With stress increase under saturated drained condition (no pore pressure), the liquid expulsion from the rock pores can enhance the closure of microcracks. This enhanced rock contacts, especially in case of pores with large aspect ratio or cracks, Vs is markedly enhanced. This pronounced effect of stress on Vs compared to Vp can be seen in Figure 1-c where data for samples under both saturated and Swi lies above the Y=X line on the plot.

Effect of Stress on Dynamic Rock Moduli

The effect of stress increase on Young's modulus (E), bulk modulus (K), and shear modulus (G) of rock samples under dry, saturated, and at Swi conditions is shown in Figure 1-d through 1-f. Figures 1-d and 1-f show that stress has significant influence on G and E for all saturation levels whereas K (Figure 1-e) is almost negligibly affected by stress variation except under dry condition. In their mathematical form both G and E are a direct function of Vs. The increase of Vs with stress increment as explained in the previous section is the main factor responsible for the dependence of G and E on stress. As K depends largely on Vp, the strong influence of stress on K under dry condition (Figure 1-e) is caused only by the closure of microcracks resulting in velocity increase with pressure. However, under saturated condition, the overall increase in K will also be contributed by the bulk modulus of pore water (~2 GPa) due to Vp increase resulting from saturation even under 500 psi. Therefore, the net increase in K due to stress increase for dry samples is expected to be more than under saturated conditions. Similar effect of stress can be observed for samples having K value less than 20 GPa under 500 psi mainly due to high porosity. The two data points for K plotted below the Y=X line in Figure 1-e were due to poor S-wave under 500 psi.

Effect of Saturation on Dynamic Rock Moduli

The dynamic moduli of the rock samples under reservoir effective stress are shown in Figure 2 for all saturation conditions. As observed in Figure 2-a and 2-c, both E and G are unaffected by saturation although E shows a slight but negligible increase. Bulk modulus, on the other hand, shows a significant increase with saturation. The relative increase in K value among these saturated samples depends on porosity.

The data in Figures 1-e and 2b, in fact, shows that some of the samples have K values higher than normally expected for pure quartz (37 GPa). Mineralogical analysis on selected groups of samples shows that the samples in the present study were having muscovite, illite, and kaolonite in varying quantities between 2% and 20% by weight. These clay minerals have K value more than 35 GPa as reported by Zhijing et. al [9]. The presence of these clay minerals can be attributed to the overall increase in K of samples above 37 GPa.

CONCLUSIONS

The following conclusions can be made from this study:

- Both stress and saturation affect the velocities and dynamic rock moduli. However, each of these two factors affects the measurements in a different way.

The objective of the use of velocity values or the dynamic rock bulk moduli for a specific application would suggest the testing conditions for acoustic measurements to be adopted in the laboratory. For instance, E is mainly required to assess the rock stiffness and is employed in many rock mechanics applications.

- The study demonstrates that not only shear modulus but Young's modulus also does not show any significant change with respect to saturation. Therefore, both of these moduli should be calculated based on measurements conducted at simulated in-situ reservoir stress conditions. Any other stress state will not yield proper values of the moduli.
- Bulk modulus is a useful indicator to study the effect of saturation on the rock behavior. Variation in stress would not cause significant variation in bulk modulus as compared to that caused by change in saturation.

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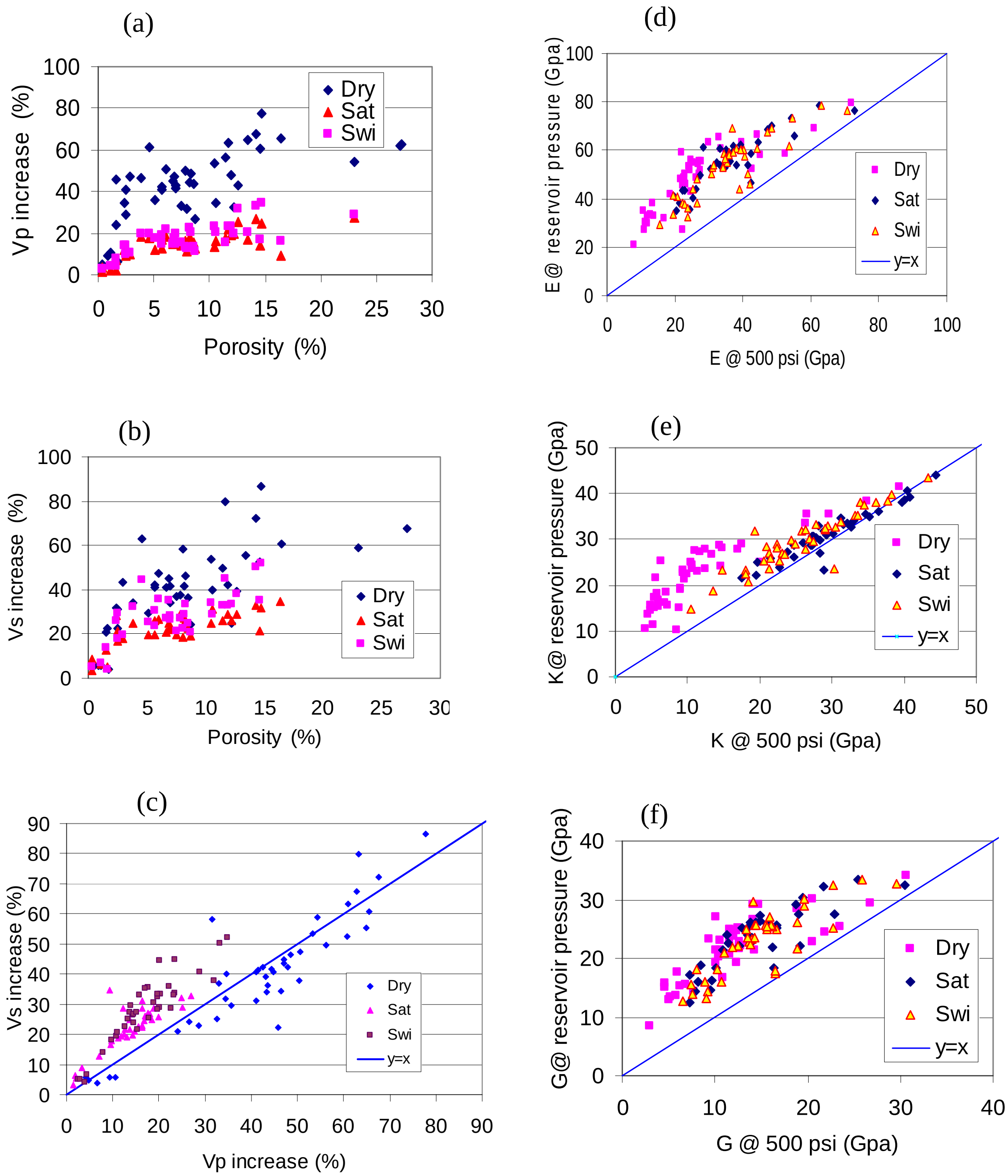

Figure1. Effect of stress on velocity increase and dynamic moduli: (a) Vp vs. porosity; (b) Vs vs. porosity; (c) Vp-Vs comparison, (d) Young's modulus, E; (e) Bulk modulus, K; and (f) Shear modulus, G.

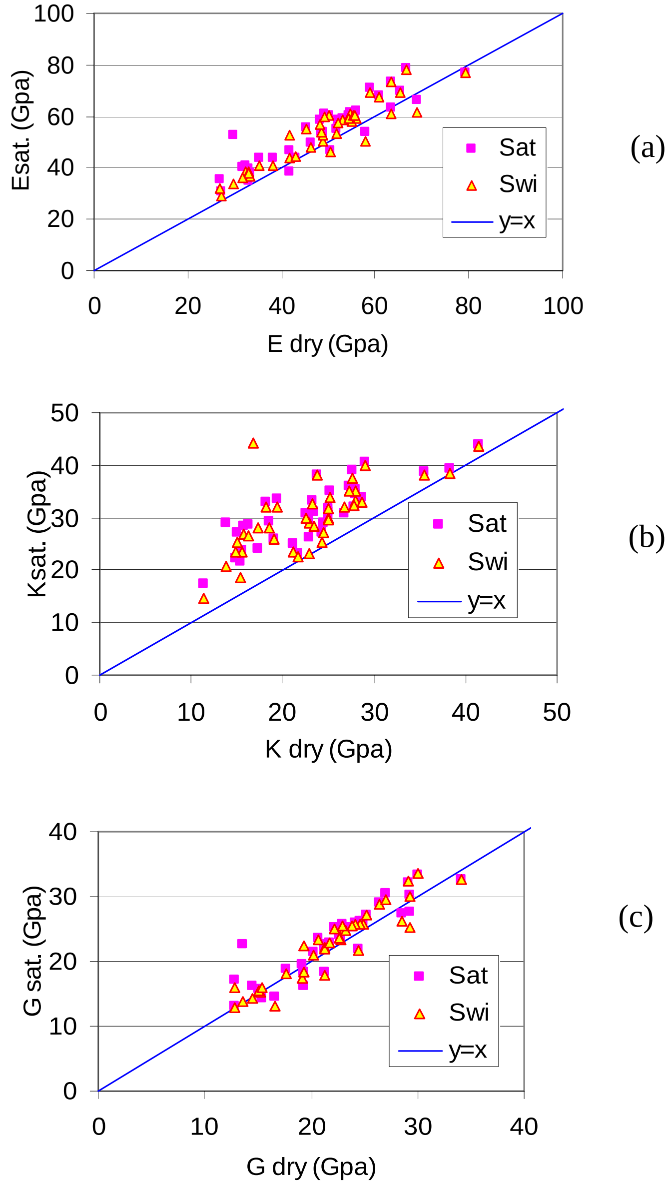

Figure 2. Effect of saturation on dynamic rock moduli under reservoir effective stress: (a) Young's modulus, E; (b) Bulk modulus, K; and (c) Shear modulus, G.