# SOUND VELOCITY OF DRILLING MUD SATURATED WITH RESERVOIR GAS

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**Abstract**

**Drillings muds are used to balance subsurface pressures, lubricate the drillstring, clean the bottom of the hole, remove cuttings and aid formation evaluation. During drilling, the mud is pumped down the drill pipe and returns via the annulus between the drill string and the formations. If the pore-fluid formation pressure exceeds that of the mud column, reservoir gas can enter the wellbore, creating a kick and causing severe damage. Knowledge of the in-situ sound velocity of drilling mud can be useful for evaluating the presence and amount of gas invasion in the drilling fluid. Technologies such as mud pulse acoustic telemetry require this information. In the following sections, we propose a model for calculating the in-situ density and sound velocity of water-based and oil-based drilling muds containing formation gas.**

## ACOUSTIC PROPERTIES OF DRILLING MUD

Let us assume a given drilling plan, where the pore pressure $p$ is provided as a function of depth $z$. The density of drilling mud required at each depth is $\bar{\rho}_{\rm mud} = p/(gz)$, where $g$ is the acceleration of gravity. However, as we shall see below, $\bar{\rho}_{\rm mud}$ is an equivalent density, since the density of the drilling mud depends on temperature and pressure through the depth $z$. Moreover, we assume a constant geothermal gradient, $G$, such that the temperature variation with depth is $T = T_0 + Gz$, with a surface temperature $T_0$. Typical values of $G$ range from 20 to 30 °C/km.

Many types of drilling mud are used in the industry. Major categories include oil-based and water- or brine-based drilling muds, with clay suspensions such as sodium montmorillonite (bentonite) and attapulgite, or salt gel, and various chemical additives. For simplicity, we consider that the mud consists of suspensions of clay (quartz) particles and high-gravity solids, such as barite (in water-based muds) and itabarite (an iron ore, in oil-based muds), whose properties are assumed temperature- and pressure-independent. We exclude aereated muds in this analysis.

The fluid properties depend on temperature and pressure, and on API number and salinity, if the fluid is oil or water, respectively. Batzle and Wang (1992) and Mavko *et al.* (1998) provide a series of useful empirical relations between the state variables and velocity and density. Moreover, oil density depends on API gravity and brine density on the content of sodium chloride.

Reuss's model is used to model the acoustic properties of drilling mud. This model describes the properties of a fluid suspension or fluid mixture. It assumes that the constituents move together, so that the composite density is simply the volume-weighted average of the densities of the constituents. The mud density is given by

$$\rho_{\rm mud} = \phi_q \rho_q + \phi_b \rho_b + (1 - \phi_q - \phi_b)\rho_f, \tag{1}$$

where $\phi_q$, $\rho_q$ and $\phi_b$, $\rho_b$ are the volume fractions and densities of the clay particles and high-gravity solid, respectively, and $\rho_f$ is the fluid density. Let us assume that the clay composition $\phi_q$ is constant. The fraction of high-gravity solids $\phi_b$, corresponding to an equivalent mud density $\bar{\rho}_{\rm mud}$ at depth $z$, is obtained from the following balance equation:

$$\int_0^z \rho_{\rm mud}(z')dz' = \bar{\rho}_{\rm mud} z, \tag{2}$$

where the depth variable $z'$ determines the temperature profile and the pressure profile according to the drilling plan.

Note that $\rho_{\rm mud}$ depends on pressure and temperature through the depth variable. It may also be noted that despite the fact that chemical interactions between the single constituents are not taken into account, the model is in very good agreement with measured data and the empirical equation proposed by Kutasov (1989) for water- and oil-based drilling muds.

Reuss's model, also called Wood's model, averages the reciprocal of the bulk moduli (isostress assumption). The composite bulk modulus of the drilling mud is obtained from

$$\frac{1}{K_{\rm mud}} = \frac{\phi_q}{K_q} + \frac{\phi_b}{K_b} + \frac{1 - \phi_q - \phi_b}{K_f}, \tag{3}$$

where $K_q$, $K_b$ and $K_f$ are the bulk moduli of clay, high-gravity solid and fluid, respectively.

## ACOUSTIC PROPERTIES OF RESERVOIR GAS

In-situ reservoir gas behaves as a real gas, which satisfies van der Waals equation:

$$(p + a\rho_g^2)(1 - b\rho_g) = \rho_g RT, \tag{4}$$

where $p$ is the gas pressure, $\rho_g$ is the gas density, $T$ is the absolute temperature and $R$ = 1.986 cal/mol °K is the gas constant. Moreover, $a$ = 0.225 Pa (m$^3$/mole)$^2$ = 879.9 MPa (cm$^3$/g)$^2$ and $b = 4.28 \times 10^{-5}$ m$^3$/mole = 2.675 cm$^3$/g (one mole of methane, $CH_4$, corresponds to 16 g). Equation (4) gives the gas density as a function of pressure and depth, if we assume that the gas pressure is equal to the expected formation pressure.

The isothermal gas compressibility $c_T$ depend on pressure. It can be calculated from van der Waals equation as

$$c_T = \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial p}$$

at constant temperature. It gives

$$c_T = \left[\frac{\rho_g RT}{(1 - b\rho_g)^2} - 2a\rho_g^2\right]^{-1}. \tag{5}$$

For sound waves below 1 GHz or so, it is a better approximation to assume that the compression is adiabatic, i.e., that the entropy content of the gas remains nearly constant during the compression. Adiabatic compressibility $c_S$ is related to isothermal compressibility $c_T$ by $c_S = \gamma c_T$, where $\gamma$ is the heat capacity ratio at constant pressure, which depends on measurable quantities. For polyatomic gases we may use the approximation $\gamma \approx \frac{4}{3}$. In this case, the gas bulk modulus can expressed as $K_g = 3/(4c_T)$. Another minor correction to the gas bulk modulus is due to the variable composition of natural gases, a correction that is important at low temperatures, 1970; Batzle and Wang, 1992). An alternative but equivalent expression for the acoustic properties of gases can be found in Batzle and Wang (1992) and Mavko *et al.* (1998).

## SOUND VELOCITY OF THE DRILLING MUD/GAS MIXTURE

Again, we use Reuss's model for the velocity of sound in a liquid/gas mixture. The composite density is

$$\rho = \phi_{\rm mud}\rho_{\rm mud} + \phi_g \rho_g, \tag{6}$$

provided that $\phi_{\rm mud} + \phi_g = 1$, and the composite bulk modulus is obtained from

$$\frac{1}{K} = \frac{\phi_{\rm mud}}{K_{\rm mud}} + \frac{\phi_g}{K_g}. \tag{7}$$

In order to model dissipation mechanisms due to the viscosity of the mud, we assume that attenuation of the sound wave is modeled by a a frequency-dependent modulus of the form

$$M(\omega) = \left[1 + \frac{2}{\pi Q}\ln\frac{\tau_2}{\tau_1}\right]\left[1 + \frac{2}{\pi Q}\ln\left(\frac{1 + i\omega\tau_2}{1 + i\omega\tau_1}\right)\right]^{-1} \tag{8}$$

where $\omega$ is the angular frequency, $\tau_1$ and $\tau_2$ are time constants, with $\tau_2 < \tau_1$, and $Q$ defines the value of the quality factor, which remains nearly constant over the selected frequency band. Equation (8) corresponds to a continuous distribution of relaxation mechanisms. For high frequencies, $M \to 1$. We assume that $Q$ is a function of gas saturation $\phi_g$:

$$Q = [4\phi_g(1 - \phi_g)]^{-\alpha} Q_{\rm min}, \tag{9}$$

where $Q_{\rm min}$ is the minimum quality factor (at midrange of saturations) and $\alpha$ is an empirical coefficient.

The sound velocity is then given by the frequency $\omega$ divided by the real part of the complex wavenumber $\omega/\bar{V}$, where $\bar{V} = \sqrt{KM/\rho}$ is the complex velocity. We obtain

$$V = \mathrm{Re}\left(\sqrt{\frac{\rho}{KM}}\right)^{-1}, \tag{10}$$

where $K$ is the unrelaxed bulk modulus. The effect of attenuation is to decrease the velocity, mainly at midrange saturations, according to the attenuation model proposed in equations (8) and (9).

**EXAMPLE**

The pore pressures for a drilling plan corresponding to a deep, relatively high pressure well are given below:

| Depth $z$, feet | Pore pressure $p$, psi | Mud weight $M_w$, lb/gal |
|---|---|---|
| 1000 | 468 | 9.0 |
| 3000 | 1404 | 9.0 |
| 5000 | 2340 | 9.0 |
| 7000 | 3276 | 9.0 |
| 9000 | 4212 | 9.0 |
| 10000 | 4836 | 9.3 |
| 11000 | 5434 | 9.5 |
| 12000 | 6115 | 9.8 |
| 14000 | 7280 | 10. |
| 16000 | 8736 | 10.5 |

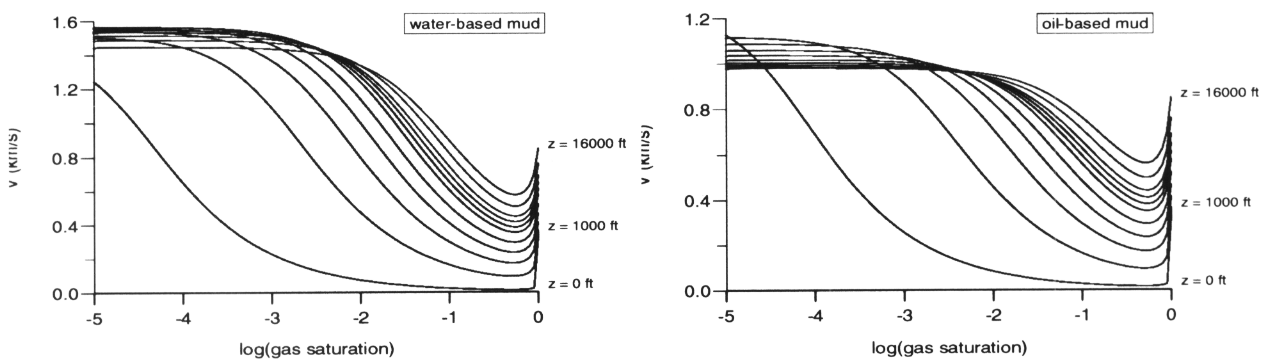
where mud weight and pressure are related by

$$p(\text{psi}) = 0.052\ M_w(\text{lb/gal})\ z(\text{feet}). \tag{11}$$

We recall that 1 MPa = 145 psi and 1 g/cm$^3$ = 8.34 lb/gal. Therefore, $\bar{\rho}_{\text{mud}}$ (g/cm$^3$) = $M_w/8.34$. The environmental conditions and material properties for calculating the acoustic properties of gas-saturated drilling mud are given in the Table .

| |
|---|
| Clay bulk modulus, $K_q$: 36 GPa. |
| Clay density, $\rho_q$: 2.65 g/cm$^3$. |
| Clay fraction, $\phi_q$: 0.03. |
| Barite bulk modulus*, $K_q$: 55 GPa. |
| Barite density, $\rho_q$: 4.2 g/cm$^3$. |
| Itabarite bulk modulus, $K_q$: 80 GPa. |
| Itabarite density, $\rho_q$: 5.1 g/cm$^3$. |
| Weight fraction of sodium chloride, $S$: 50000 ppm/10$^6$. |
| API gravity of oil, API: 50 deg. |
| Lower relaxation time, $\tau_1$: 0.1 s. |
| Upper relaxation time, $\tau_1$: 1000 s. |
| Minimum quality factor, $Q_{\min}$: 50. |
| Attenuation coefficient, $\alpha$: 1. |
| Atmospheric pressure, $p_0$: 0.1 MPa. |
| Acceleration of gravity, $g$: 9.81 m/s$^2$. |
| Surface temperature, $T_0$: 25 $^o$C. |
| Geothermal gradient, $G$: 30 $^o$C/km. |

Solving equation (2), the water-based mud requires a fraction of barite ranging from 0 % for 1000 feet to 6.4 % for 16000 feet, in order to balance the formation pressure. The range of itabarite for the oil-based mud is 5.6 % for 1000 feet to 10.4 % for 16000 feet.




The Figure shows the sound velocities of water-based drilling mud and oil-based drilling muds versus gas saturation at different depths, for a frequency of 25 Hz. Also shown is the velocity at atmospheric pressure $p_0$ and temperature $T_0$ ($z = 0$). This curve decreases rapidly with increasing gas saturation due to the low value of the gas bulk modulus at atmospheric pressure. At full gas saturation, the composite density is that of the gas, and the velocity increases approximately to the velocity of sound in air. Gas at higher depths, and therefore at higher pressure and temperature, has a higher velocity due to the increase in density and bulk modulus.

## CONCLUSIONS

We calculated the variations in drilling-mud velocity when formation gas enters the wellbore at a given drilling depth. Drilling muds were modeled as a suspension of clay particles and high-gravity solids in water or oil, with the acoustic properties of these fluids depending on pressure and temperature. Since mud at different depths experiences different pressures and temperatures, downhole mud-weights can be significantly different from those measured at the surface. Taking this fact into consideration, we assumed constant clay composition and obtained the fraction of high-gravity solids to balance the formation pressure corresponding to a given drilling plan. This gave the in-situ density of the drilling mud, which together with the bulk moduli of the single constituents allowed us to compute the sound velocity using Reuss's model. A phenomenological model based on a continuous spectrum of relaxation mechanisms was used to describe attenuation due to mud viscosity. The calculations for water-based and oil-based muds showed that the sound velocity is strongly dependent on gas saturation and drilling depth.

## REFERENCES

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