An Acoustic Velocity Model for Heavy Oil Sand

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An acoustic velocity model for heavy-oil sand

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The modified Contact Cement Theory (CCT) is applied to predict the acoustic velocities of heavy oil sand in this paper. The existence of contact thickness in the heavy oil sand reduces its moduli and acoustic velocities, which is ignored in the original CCT. To take into account this effect, the modified CCT is adopted in this paper and its approximation is obtained to simplify its application. Using this approximation, the acoustic velocities of the heavy oil sand in Xinjiang Oil Field are predicted. The results show that without considering the effects of contact thickness, the acoustic velocities will be largely overestimated. By using the modified CCT, the influence of contact thickness is considered and the accuracy for the acoustic velocities prediction of heavy oil sand improves greatly.

Introduction

As one kind of unconventional resources, heavy oil has enormous amount and is being exploited actively recently. For the heavy oil production, thermal recovery methods are proved to be the most efficient in the current industry practice. To improve the efficiency of recovery, reservoir characterization and production monitoring of heavy oil are necessary. As with conventional oil and gas, acoustic logging technology is important for the reservoir characterization and production monitoring of heavy oil. However, due to the special properties of the heavy oil, it is difficult to link the acoustic velocity measured to the physical properties of the heavy oil sand. Therefore, a proper acoustic velocity model is needed to correlate them.

For the heavy oil sand, the sand grains are usually cemented by the heavy oil and other cements. Therefore, the corresponding acoustic velocity model should consider the effects of the cementation on the acoustic velocity of the heavy oil sand. To this end, the Contact Cement Theory (CCT) has been proposed by Dvorkin et al. (1994) to model this effect. This theory has been successfully applied to the high-porosity sandstone with weak cementation. However, it is found that the effects of contact thickness on the acoustic velocities are ignored in this theory. Without considering the influence of contact thickness, the acoustic velocities could be largely overestimated when the sand grains don't contact each other (Han et al., 2014). To solve this problem, a modified CCT was proposed by Han and Guo (2014). By considering the effects of contact thickness, the very low acoustic velocities of loose sand with no direct grain contact are properly predicted.

The grains in the heavy oil sand usually don't contact each other due to the low compaction rate at the shallow burial depth. Therefore, the modified CCT can be used to predict its acoustic velocities. In this paper, we first briefly introduce the modified CCT. Then, a numerical approximation for this theory is obtained to simplify its application. Finally, we apply this approximation to predict the acoustic velocities of the heavy oil sand of Xinjiang Oil Field in China.

Modified CCT

The CCT was proposed by Dvorkin et al. (1994), which estimates the elastic properties and the acoustic velocities of loose sand with weak cementation. This theory was derived based on the grain-cement contact model, as shown in Figure 1.

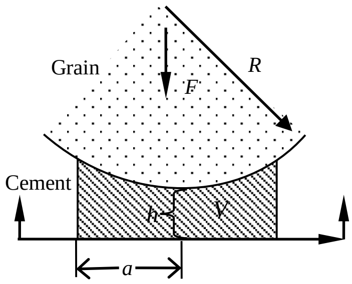


Figure 1 *Contact model of CCT. F: applied force; R: grain radius; a: cementation radius; h: contact thickness; V: volume of the cement.*

Through the mechanical relationship between the grain and the cement, the normal stiffness, S_n, and tangential stiffness, S_τ, were derived as follows (Dvorkin et al., 1994):

$$S_n = -\frac{4\pi R G_c (1-v_c)}{1-2v_c}\frac{k_n}{\Delta_n} \qquad S_\tau = -2\pi R G_c \frac{k_\tau}{\Delta_\tau} \qquad k_n = \int_0^\alpha \frac{H_n(t)tdt}{\varepsilon + t^2/2} \qquad k_\tau = \int_0^\alpha \frac{H_\tau(t)tdt}{\varepsilon + t^2/2} \tag{1}$$

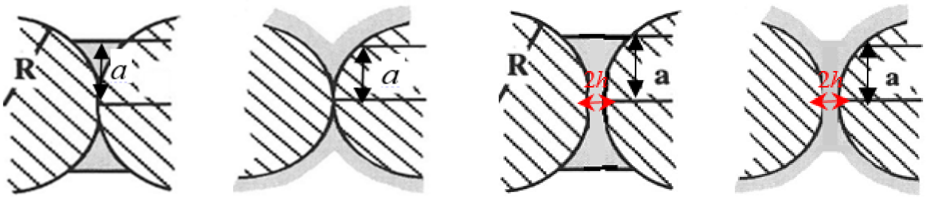
where G_c is the shear modulus of the cement; v_c is the Poisson's ratio of the cement; k_n and k_τ are proportional to the normal force and tangential force, respectively; Δ_n and Δ_τ are the overall normal and tangential deformation, respectively; $H_n(t)$ and $H_\tau(t)$ are the normal and tangential deformation of the cement, respectively; ε is the ratio of the contact thickness h to the radius of the grain R (normalized contact thickness); α is the ratio of the cementation radius a to the radius of the grain R (normalized cementation radius).

The elastic moduli and the acoustic velocities of the dry cemented sand can then be calculated as follows (Dvorkin et al., 1994):

$$K_{eff} = \frac{n(1-\phi_0)}{12\pi R(1+\varepsilon)} S_n \quad G_{eff} = \frac{n(1-\phi_0)}{20\pi R(1+\varepsilon)} (S_n + \frac{3}{2} S_\tau) \quad V_p = \sqrt{(K_{eff} + {}^4\!/_3 G_{eff}) / \rho} \quad V_s = \sqrt{G_{eff} / \rho} \tag{2}$$

where n is the coordination number; Φ_0 is the critical porosity; K_{eff} and G_{eff} are the bulk and shear moduli of the loose sandstone; V_p and V_s are the compressional and shear wave velocities of the loose sandstone, respectively.

Equation 1 and 2 show that, the normalized cementation radius α is needed for the calculation of moduli and acoustic velocities. To obtain this parameter, two schemes of cementation are considered (Dvorkin and Nur, 1996), as shown in Figure 2.



(a) (b) (c) (d)

Figure 2 *Two schemes of cementation. (a) and (c) Cement only accumulates at the grain contacts. (b) and (d) Cement distributes evenly around the grains. Note that the contact thickness is zero for (a) and (b), but not zero for (c) and (d).*

By assuming zero contact thickness, i.e., the sand grain contacts each other (Figure 2a and 2b), the normalized cementation radius α are given as follows (Dvorkin and Nur, 1996):

$$\text{Scheme a: } \alpha = 2[\frac{\phi_0 - \phi}{3n(1-\phi_0)}]^{0.25} \quad \text{Scheme b: } \alpha = [\frac{2(\phi_0 - \phi)}{3(1-\phi_0)}]^{0.5} \tag{3}$$

Without considering the influence of the contact thickness, Equation 3 can't be applied when the grain doesn't contact each other (non-zero contact thickness, as shown in Figure 2c and 2d). For this reason, Han and Guo (2014) derived the new expressions for the cementation radius by considering the effects of contact thickness. They are as follows:

$$\text{Scheme a: } \alpha = \sqrt{-2\frac{h}{R} + 2\sqrt{(\frac{h}{R})^2 + \frac{4}{3n}\frac{\phi_0 - \phi}{1-\phi_0}}} \quad \text{Scheme b: } \alpha = [\frac{2(\phi_0 - \phi)}{3(1-\phi_0)}]^{0.5} \tag{4}$$

The influence of contact thickness on the cementation radius can be clearly seen for Scheme a. However, this influence is negligible for Scheme b. It should be noted that this doesn't mean the contact thickness doesn't influence the moduli and acoustic velocities for Scheme b. It is because the influence of the contact thickness on the moduli and acoustic velocities is not only through the cementation radius, it also has direct influence on them, as shown in Equation 1 and 2. The CCT is modified by replacing Equation 3 with Equation 4, then it can be applied for the case with non-zero contact thickness. In the heavy oil sand, the contact thickness is usually not zero due to the low compaction rate. The gaps between the sand grains are normally filled with heavy oil and other cements. Therefore, the modified CCT can be used to predict its acoustic velocities.

Approximation for the modified CCT

We can apply the modified CCT directly to predict the acoustic velocities of heavy oil sand. However, it needs a lot of time to obtain the results due to the integration involved in the calculation. Therefore, a numerical approximation is required to improve the calculation efficiency. Using the statistical method, a good approximation is given as follows:

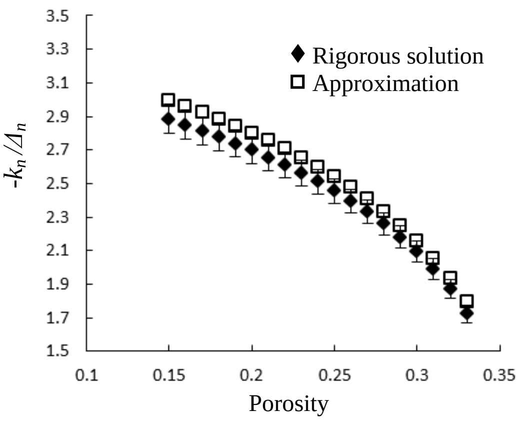
$$K_{eff} = \frac{G_c(1-v_c)}{1-2v_c}\frac{n(1-\phi_0)}{3(1+\varepsilon)}\left(-\frac{k_n}{\Delta_n}\right) \qquad G_{eff} = 0.6K_{eff} + G_c\frac{3C(1-\phi_0)}{20(1+\varepsilon)}\left(-\frac{k_\tau}{\Delta_\tau}\right)$$

$$-K_n/\Delta_n = A_n(\Lambda_n,\varepsilon)\alpha^2 + B_n(\Lambda_n,\varepsilon)\alpha + C_n(\Lambda_n,\varepsilon) \quad -K_\tau/\Delta_\tau = A_\tau(\Lambda_\tau,\varepsilon)\alpha^2 + B_\tau(\Lambda_\tau,\varepsilon)\alpha + C_\tau(\Lambda_\tau,\varepsilon) \tag{5}$$

$$A_n = -(-43\varepsilon^2 + 8.5493\varepsilon + 0.1451)\Lambda_n^{(2.381\varepsilon^2+14.445\varepsilon-0.7159)} \qquad A_\tau = -(124.33\varepsilon^2 - 30.79\varepsilon + 1.9189)\Lambda_\tau^{(-109.21\varepsilon^2+0.5713\varepsilon-0.1583)}$$
$$B_n = (-276.67\varepsilon^2 + 24.839\varepsilon + 0.4696)\Lambda_n^{(-95.238\varepsilon^2+11.605\varepsilon-0.5706)} \qquad B_\tau = (-407.4\varepsilon^2 + 1.1729\varepsilon + 3.2628)\Lambda_\tau^{(-51.498\varepsilon^2+5.2906\varepsilon-0.1819)}$$
$$C_n = -(-9.2381\varepsilon^2 + 1.8876\varepsilon - 0.0145)\Lambda_n^{(-472.38\varepsilon^2+38.719\varepsilon-1.1876)} \qquad C_\tau = -(-147.98\varepsilon^2 + 11.199\varepsilon - 0.018)\Lambda_\tau^{(-128.33\varepsilon^2+11.621\varepsilon-0.3323)}$$

$$\Lambda_n = \frac{2G_c}{\pi G}\frac{(1-v)(1-v_c)}{1-2v_c} \qquad \Lambda_\tau = \frac{G_c}{\pi G} \qquad \Lambda_n \in [0.007 - 0.04] \quad \Lambda_\tau \in [0.0007 - 0.014]$$

Due to the space limitation, Equation 5 only shows part of the approximation. The completed version of the approximation will be given in the future paper. The correlation coefficient between the approximation and the rigorous theory solutions is larger than 0.98 and the error doesn't exceed 3%, as shown in Figure 3.



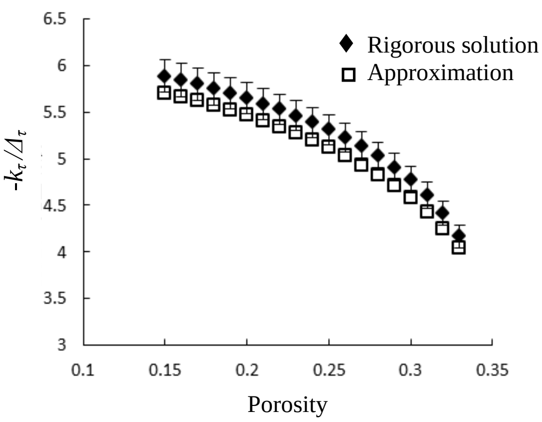


Figure 3 *Comparison between the approximation and the rigorous theory solutions.*

Application

In this section, the acoustic velocities data of heavy oil sand from Xinjiang Oil Field of China are analysed using the modified CCT. The sand grains are cemented by the mixture of heavy oil and other cements, such as kaolinite and illite. The temperature at the depth of the heavy oil sand formation (350 m – 425 m) is close to 20 ℃. At such temperature, the bulk and shear moduli of the heavy oil is about 3.2 GPa and 0.9 GPa, based on Batzle's measurement (Batzle et al., 2004). Combined with the moduli and percentage of the other cements, the bulk and shear moduli of the cement mixture are calculated to be around 4.6 GPa and 1.8 GPa, respectively. The cement mixture is distributed as Scheme a. The bulk and shear moduli of the sand grains are 38 GPa and 44 GPa, respectively. The density and porosity of the heavy oil sand are shown in Figure 4. According to the porosity distribution, the critical porosity is assumed to be 40 %, with the coordination number to be 8.5. The normalized contact thickness (ε) is obtained from the thin section, whose value is about 0.04. The bulk modulus of the formation water is 2.7 GPa. Using these parameters, the dry moduli of the heavy oil sand are calculated using the approximation for the modified CCT and the fluid saturation effect on the moduli is analysed using

Gassmann Equation. Then the acoustic velocities are calculated using the moduli and density. The results are shown in Figure 4. To illustrate the influence of the contact thickness on the acoustic velocities, the results with zero contact thickness are also shown.

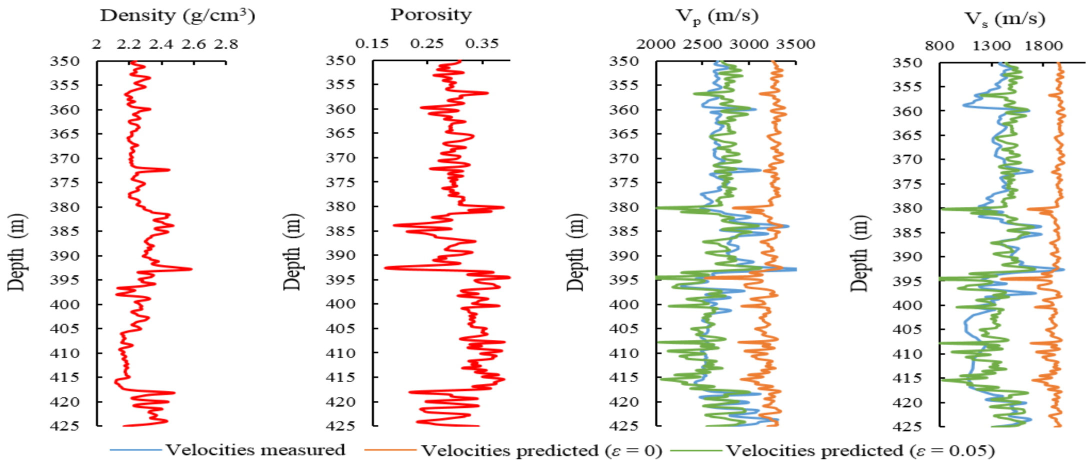


Figure 4 *Density, porosity, and acoustic velocities measured and predicted.*

It is found from Figure 4 that without considering the effects of contact thickness, the acoustic velocities will be overestimated. This is because the existence of the contact thickness reduces the normal and tangential stiffness, which results in the decrease of moduli and acoustic velocities. The accuracy of the prediction improves greatly after considering the influence of the contact thickness.

Conclusions

The modified CCT is applied in this paper to predict the acoustic velocities of heavy oil sand. For the heavy oil sand, the grains usually don't contact each other due to the low compaction rate at the shallow burial depth. The contact thickness exists between the grains. The original CCT ignores the influence of the contact thickness, which results in the overestimation of the acoustic velocities. By considering the influence of the contact thickness, the acoustic velocities measured are well predicted by the modified CCT.

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