The influence of in-situ stress and geomechanical properties on P-wave reflection coefficients for HTI media

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Abstract

Estimation of stress and geomechanical properties of anisotropic fractured reservoirs is a critical issue during oil & gas field development. Since the seismic data is sensitive to these properties, studies of the variation of P-wave reflection coefficients with azimuth in a horizontal transverse isotropic (HTI) media can be applied to obtain fracture properties and extended to estimate the in-situ principal stresses. Therefore, considering the Rüger reflectivity approximation for HTI media, we employ a seismic to geomechanics relation through the Linear Slip Theory (LST), based on a simplified Hooke's law for HTI media, to estimate fracture properties. Finally, we derive an anisotropic poroelastic horizontal stress model in order to analyze the influence of in-situ principal stresses in the AVO response for an ISO-HTI interface at the symmetry-axis and isotropy planes.

Introduction

A reliable in-situ stress and rock mechanical properties determination have always been important for all geomechanical evaluation and development of a reservoir. Accurate estimations of these properties are critical to optimize the initial drilling, infill drilling, fracturing, sand prediction, well integrity and fault reactivation evaluation during production and/or injection.

Currently, the development of techniques based on seismic data allows the estimative of spatial and temporal geomechanical properties and in-situ stress of the subsurface. Rüger (1997), for example, developed a linearized P-wave reflectivity approximation for HTI media, described in terms of isotropic elastic properties and anisotropic Thomsen's parameters $\epsilon^{(V)}$, $\delta^{(V)}$ and γ. These Thomsen's parameters can be related to fractured reservoirs properties through rock physics models.

Considering a physical modeling based on a simplification of Hooke's law for an HTI media, the Linear Slip Theory (LST) expresses anisotropic relations between Thomsen's parameters and fractured reservoirs properties. This model includes the effects of fractures by writing the effective compliance tensor of the rock as the sum of the compliance tensor of the isotropic background and the compliance tensor for the set of vertically aligned fractures (Schoenberg and Sayers, 1995; Bakulin et al., 2000).

As the rocks in the subsurface are undergoing elastic deformation, Gray et al. (2012) derived an anisotropic poroelastic horizontal stress model based on simplifications of Hooke's law assuming that rocks are constrained horizontally. This model considers the LST compliance tensor to include the effect of a set of vertical fractures on the magnitudes of the minimum and maximum principal horizontal stresses.

Therefore, considering the direct link among in-situ stress, fracture properties and P-wave reflectivity responses in anisotropic HTI environments, we did a sensitivity analysis of the influence of in-situ stresses and geomechanical properties on P-wave reflection coefficient in an ISO-HTI interface at the isotropy and symmetry/anisotropy planes.

P-wave reflection for HTI media

The HTI medium is characterized by a horizontal axis of rotational symmetry and two vertical symmetry planes: the plane formed by the symmetry axis, called symmetry-axis plane, and the plane perpendicular to the symmetry axis, called isotropy plane (Fig. 1).

Physically, the HTI symmetry can be correlated with a sequence of dipping shales and/or a system of parallel vertical cracks/fractures embedded in an isotropic matrix. When the HTI symmetry is caused by a set of vertical fractures, the isotropy plane coincides with the fracture plane.

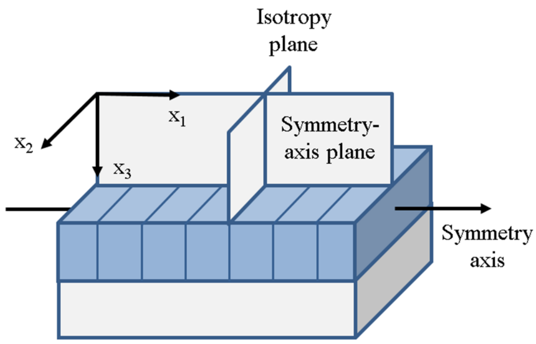

Figure 1: Representation of an HTI media showing two vertical planes, the symmetry-axis plane and the isotropy plane.

Rüger (1998) presented a linearized approximation for P-P reflection coefficient in an interface between two HTI media with the same symmetry axis alignment for weak anisotropic case:

$$R_{PP}(i,\phi) = \frac{1}{2}\frac{\Delta Z}{\bar{Z}} + \frac{1}{2}\left\{\frac{\Delta\alpha}{\bar{\alpha}} - \left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2 \frac{\Delta G}{\bar{G}} + \left[\Delta\delta^{(V)} + 2\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2 \Delta\gamma\right] cos^2\phi\right\} sin^2 i + \frac{1}{2}\left\{\frac{\Delta\alpha}{\bar{\alpha}} + \Delta\epsilon^{(V)} cos^4\phi + \Delta\delta^{(V)} sin^2\phi cos^2\phi\right\} sin^2 i \, tan^2 i, \quad (1)$$

where i denotes the incidence angle and ϕ the azimuthal angle with the symmetry-axis plane. The Δ indicates a difference and the overbar indicates an average of the corresponding properties across the boundary. The parameters β and α are the isotropy-plane velocities of the fast vertical shear-wave (polarized parallel to de isotropy plane) and the vertical compressional wave, respectively. The parameter G indicates the vertical shear modulus and Z denotes vertical P-wave impedance.

The parameters $\epsilon^{(V)}$ and $\delta^{(V)}$ denote the anisotropic Thomsen's coefficients introduced by Rüger (1997), where the subscript $^{(V)}$ symbolize the symmetric analogy assumption with Thomsen's (1986) parameters for VTI media, and γ corresponds to the generic Thomsen's parameter defined with respect to the horizontal symmetry axis.

The differences in the anisotropy Thomsen's parameters across the boundary are written as $\Delta\delta^{(v)} = (\delta^{(v)}{}_2 - \delta^{(v)}{}_1)$, $\Delta\epsilon^{(V)} = (\epsilon^{(v)}{}_2 - \epsilon^{(v)}{}_1)$ and $\Delta\gamma = (\gamma_2 - \gamma_1)$. The parameter $\Delta\delta^{(v)}$, present in $sin^2 i$ term, describes the influence of anisotropy on the small-angle reflection coefficient and the AVO slope, while $\Delta\epsilon^{(v)}$, present in $sin^2 i \, tan^2 i$ term, is more dominant at larger incidence angles. For an ISO-HTI interface (Fig. 2), $\Delta\epsilon^{(v)}$ reduces to only $\epsilon^{(v)}{}_2$, with respect to the HTI medium, considering $\epsilon^{(v)}{}_1 = 0$ for the isotropic media. The same assumption is valid for $\Delta\delta^{(v)}$ and $\Delta\gamma$.

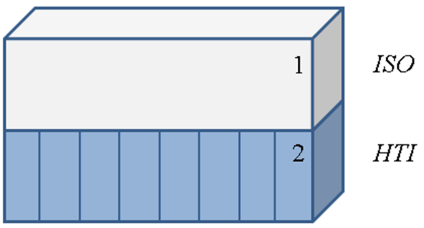

Figure 2: Interface model used to study the differences in the AVO anisotropic response with the in-situ stress influence.

The approximation described in equation (1) is linearized in small, relative differences of the isotropic elastic properties and anisotropic Thomsen's parameters and is valid for incidence angles not too close to the critical angle (Rüger, 1998).

The Linear Slip Theory (LST)

The Linear Slip Theory (LST) developed by Schoenberg and Sayers (1995) is a simple method to include the effects of vertical fractures on the seismic wave propagation through the rocks. To model these effects, the effective compliance tensor of the fractured rock is described as the sum of the compliance tensor of the unfractured background and the compliance tensor for the set of vertically parallel fractures. Using this theory, the Hooke's law can be simplified to (using Voigt notation):

$$\varepsilon_i = \{S_b + S_f\}\sigma_j, \quad (2)$$

where, ε_i are the strains, σ_j the stresses in the rock, S_b represents the compliance of the background rock and S_f the compliance of the fractures and micro-fractures in the rock (Schoenberg and Sayers, 1995).

For a single set of rotationally invariant fractures in an isotropic background, the medium becomes an HTI media with symmetry axis perpendicular to the fractures, and the compliance matrix is given by:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix} = \begin{bmatrix} \frac{1}{E}+Z_N & \frac{-\nu}{E} & \frac{-\nu}{E} & 0 & 0 & 0\\ \frac{-\nu}{E} & \frac{1}{E} & \frac{-\nu}{E} & 0 & 0 & 0\\ \frac{-\nu}{E} & \frac{-\nu}{E} & \frac{1}{E} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{\mu} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{\mu}+Z_T & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\mu}+Z_T \end{bmatrix} \begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix}, \quad (3)$$

where E, ν and μ are the Young's modulus, the Poisson's ratio and the shear modulus of the isotropic background, respectively. The parameter Z_N represents the normal fracture compliance and Z_T the tangential one.

The normal strain component, perpendicular to the fracture, is related to the material's normal compliance Z_N, while the shear strain components, tangential to the fracture, are related to the material's tangential compliance Z_T. The compliance matrix, that represents the inverse of stiffness, is defined as the ability of an object to yield elastically when a force is applied (Gray et al., 2012).

Following the LST model, HTI anisotropic expressions for Thomsen's parameters $\epsilon^{(V)}$, $\delta^{(V)}$ and γ, in terms of the fracture weaknesses, can be derived in a straightforward way from equation (3). Bakulin et al. (2000) show these linearized expressions with respect to Δ_N and Δ_T (normalized normal and tangential compliances), under the assumption of weak anisotropy, to gain insight into the relationship between the anisotropic coefficients and the fracture weaknesses:

$$\epsilon^{(V)} = -2g(1-g)\Delta_{N,} \quad (4)$$

$$\delta^{(V)} = -2g[(1-g)\Delta_N + \Delta_T], \quad (5)$$

$$\gamma^{(V)} = -\frac{\Delta_T}{2}, \quad (6)$$

where the parameter g represents the squared velocity ratio ($g = \beta^2/\alpha^2$).

The parameter $\gamma^{(V)}$ is related to the generic parameter γ, defined with respect to the horizontal symmetry axis, as:

$$\gamma^{(V)} = -\frac{\gamma}{1+2\gamma}. \quad (7)$$

Since the squared velocity ratio g < 0.5, we infer from equations (4)–(6), that $\epsilon^{(V)}$, $\delta^{(V)}$ and $\gamma^{(V)}$ for vertical fractures are nonpositive:

$$\epsilon^{(V)} \leq 0, \quad \delta^{(V)} \leq 0, \text{and } \gamma^{(V)} \leq 0. \quad (8)$$

The relation between the normalized normal compliance Δ_N and the normal compliance Z_N is given by (Schoenberg and Sayers, 1995):

$$\Delta_N = \frac{Z_N E(1-\nu)}{(1+\nu)(1-2\nu)+Z_N E(1-\nu)}. \quad (9)$$

The anisotropic poroelastic horizontal stress model

Assuming that rocks are constrained horizontally and undergoing elastic deformation, it is possible to derive expressions to estimate the magnitude of principal horizontal stresses based on simplified Hooke's law considering the LST compliance tensor (Gray et al., 2012).

Hence, assuming that one principal stress is vertical, so the other two are horizontal, equation (3) can be used to write the horizontal strains as function of these stresses. Given the assumption that the rocks are in a poroelastic domain and constrained horizontally, the horizontal strains ε_h and ε_H are equal to zero:

$$\varepsilon_h = \left(\frac{1}{E} + Z_N\right)\sigma'_h - \frac{\nu}{E}(\sigma'_H + \sigma'_v) = 0, \quad (10)$$

and

$$\varepsilon_H = \frac{1}{E}\sigma'_H - \frac{\nu}{E}(\sigma'_h + \sigma'_v) = 0, \quad (11)$$

where σ'_v represents the effective vertical stress, and σ'_h and σ'_H the minimum and maximum effective horizontal stress, respectively. The effective term expresses the difference between the absolute stress and the pore pressure.

Rearranging the equations (10) and (11) for the effective horizontal stresses:

$$\sigma'_h = \sigma'_v \frac{\nu(1+\nu)}{1+EZ_N-\nu^2}, \quad (12)$$

and

$$\sigma'_H = \sigma'_v \nu \frac{1+EZ_N+\nu}{1+EZ_N-\nu^2}. \quad (13)$$

The elastic parameters for equations (12) and (13) can be derived from seismic data, e.g., Mallick (1995) and Gray, (2005). The Z_N parameter can be estimated from azimuthal seismic inversion, e.g., Downton and Roure (2010), and the vertical stress is obtained by integrating logged density over depth or from integrating density obtained from seismic inversion.

For this sensitivity analysis, rearranging the equation (12) for the Z_N compliance:

$$Z_N = \frac{\frac{\sigma'_v}{\sigma'_h}\nu(1+\nu)+\nu^2-1}{E}, \quad (14)$$

and substituting the equation (14) in (9), and finally substituting (9) in (4), we obtain an expression relating the ratio between vertical and horizontal effective stress (σ'_v/σ'_h) with Thomsen's parameter $\epsilon^{(V)}$, which is used to estimate the P-P reflection coefficients by equation (1). We highlight that for each in-situ stress scenario a different fractured media is achieved, generating a new azimuthal AVO response.

The influence of in-situ stresses on P-wave reflection coefficients for HTI media

According to the relations between Thomsen's parameters and in-situ stresses and their direct link with the reflection coefficients in an HTI medium, we analyze the sensitivity of P-wave reflection in an ISO-HTI interface at the isotropy and symmetry/anisotropy planes varying the minimum horizontal stress.

The Table 1 lists the elastic parameters used for the ISO-HTI interface model (Fig. 2) at 2500 m with absolute vertical stress (overburden) σ_v = 66.3 MPa, hydrostatic pore pressure P_p = 25.5 MPa and symmetry-axis plane azimuth equal 30°.

Table 1: Elastic parameters used to analyze the azimuthally AVO response.

Property	ISO layer	HTI layer
α (m/s)	3302	3650
β (m/s)	1807	1900
ρ (kg/m^3)	2700	2700

Following the formulations previously described, we vary the ratio between absolute minimum horizontal and absolute vertical stresses (σ_h/σ_v) from 0.570 to 0.665, considering a fixed value for σ_v = 66.3 MPa, as observed in the Table 2.

The stress polygon in Fig. 3, following the state of crustal stress in frictional equilibrium theory, indicates that these horizontal to vertical stress ratios, as well as their respective absolute stress magnitudes (Table 2), will be inside a pure normal faulting domain (Zoback, 1984, 2010, 2017), as indicated by the red rectangle.

The Thomsen's parameter $\epsilon^{(V)}$ was computed combining the equations (14), (9) and (4), and we assume $\delta^{(V)}$ equal to $\epsilon^{(V)}$ and fix γ equal to zero. The Thomsen's parameters used during this analysis are representative of an HTI media with anisotropy guided by the presence of dry fractures or dry cracks, as reported by Rüger (1997).

The isotropic elastic parameters E and ν, necessary to $\epsilon^{(V)}$ estimation, were computed through conventional linear elastic equations in function of compressional and shear vertical velocities for each layer.

Table 2: Stress sensitivity results using fixed elastic parameters defined in Table 1.

σ_h/σ_v	σ_v (MPa)	σ_h (MPa)	σ_H (MPa)	σ_H/σ_v	σ_h/σ_H	$\epsilon^{(v)}$	α_{iso} (m/s)	α_{ani} (m/s)
0,570	66,3	37,8	42,2	0,64	0,90	-0,157	3650	3077
0,590	66,3	39,1	42,6	0,64	0,92	-0,127	3650	3188
0,610	66,3	40,4	43,0	0,65	0,94	-0,095	3650	3302
0,630	66,3	41,7	43,4	0,66	0,96	-0,063	3650	3421
0,650	66,3	43,1	43,8	0,66	0,98	-0,029	3650	3544
0,665	66,3	44,1	44,1	0,67	1,00	-0,003	3650	3640

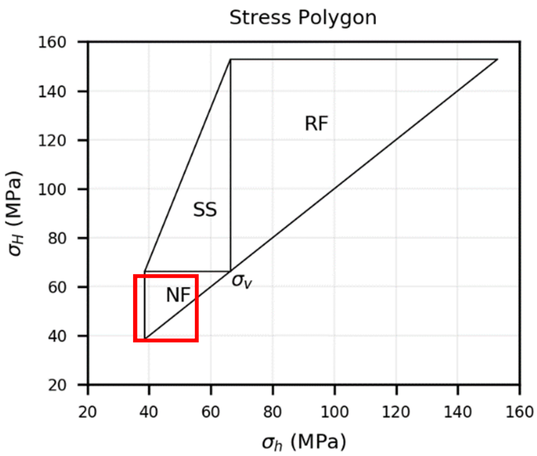

Figure 3: Stress polygon constructed using the state of crustal stress in frictional equilibrium theory and Anderson's fault classification. The input parameters are: absolute vertical stress (overburden) σ_v = 66,3 MPa, pore pressure P_p = 25,5 MPa, and friction coefficient μ = 0,6. The NF denotes normal faulting, SS strike slip, and RF reverse faulting.

The analysis of the influence of in-situ stresses on anisotropic P-wave reflections follows the next steps:

1. Create the velocity model using parameters defined in Table 1;

2. Fix the overburden and pore pressure, introducing σ_h/σ_v values from 0.570 to 0.665 in order to compute σ_h directly from these ratios (computed values of σ_h listed in Table 2);

3. Compute Z_N and Δ_N using equations (14) and (9), respectively. The isotropic elastic parameters v and E were fixed for the host rock and computed through conventional linear elastic equations;

4. Compute the Thomsen's parameter $\epsilon^{(V)}$ from Δ_N using the equation (4). Next, compute the anisotropic horizontal velocity α_{ani} using equation (15), considering the incidence angle i = 90°, the vertical velocity α_{iso} and the Thomsen's parameters (Thomsen, 1986):

$$\alpha(i) = \alpha_{iso}\left[1 + \delta^{(V)} sin^2 i \, cos^2 i + \epsilon^{(V)} sin^4 i\right]; \qquad (15)$$

5. Compute the maximum horizontal absolute stress σ_H using equation (13);

6. Compute the P-wave reflectivity with equation (1) using the Thomsen's parameter $\epsilon^{(V)}$ computed in the step 4, assuming $\epsilon^{(V)} = \delta^{(V)}$ and γ = 0, at the isotropy and symmetry/anisotropy planes.

The P-wave reflection responses for each in-situ stress scenarios are shown in Fig. 4. It is observed a considerable departure between the AVO signature at the symmetry-axis (anisotropic) and isotropic planes when some degree of differences between the minimum and maximum horizontal stress exists. This effect is present in each plot in Fig. 4 and decreases when the ratio σ_h/σ_v varies from 0.570 to 0.665.

The departure decreasing is related to the facture normal compliance magnitude, which can be associated with the $\epsilon^{(V)}$ values by equation (4). As shown in Table 2, for the first stress case ($\epsilon^{(V)}$ = -0,157), the effect of fractures is emphasized, causing the highest differences between minimum and maximum horizontal stresses and between the velocities α_{iso} and α_{ani}, consequently, occurs the major departure between the AVO signatures, even in near offsets.

As the effect of the fracture compliance is reduced ($\epsilon^{(V)}$ varying from -0,157 to -0,003) the rock tends to become isotropic, so that the minimum and maximum horizontal stress tend to be equal, as well as the compressional velocities α_{iso} and α_{ani}. This effect decreases the departure between the AVO signatures and for near offsets is almost imperceptible.

Analyzing the last stress scenario ($\epsilon^{(V)}$ = -0,003), it is possible to see the effect of equal horizontal stress, where no more difference between near/long offsets is observed. In this case, the fracture normal compliance tends to be zero, and the rock becomes isotropic.

Must be considered that the dominant kind of anisotropy is guided by the presence of fractures, following the Hooke's law and the LST model. It could explain the small differences between the minimum and maximum horizontal stress magnitudes for all cases, as showed in Table 2.

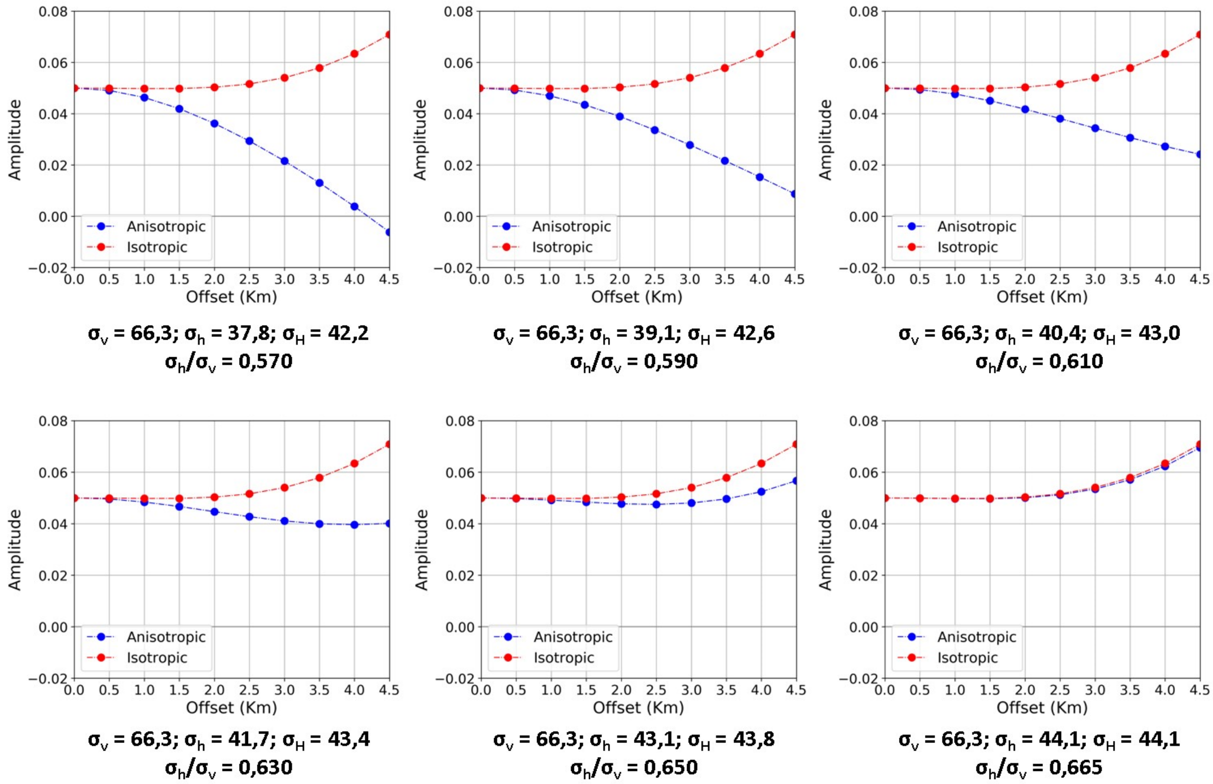

Figure 4: Reflection coefficient responses in function of different horizontal stress scenarios following the anisotropic poroelastic HTI model.

Conclusions and Recommendations

For this analysis we employ a seismic to geomechanics relation through the Linear Slip Theory (LST) to analyze the influence of in-situ stresses and geomechanical properties on P-wave reflection coefficient in an ISO-HTI interface at the isotropy and symmetry/anisotropy planes.

The assumed values for the Thomsen's parameters used during this analysis are representative of an HTI media with anisotropy guided by the presence of dry fractures or dry cracks as reported by Rüger (1997). This assumption could explain the short differences between the minimum and maximum horizontal stress magnitudes, representing a normal faulting domain.

The departure between the AVO signature at the symmetry-axis (anisotropic) and isotropic planes is related to the facture normal compliance magnitude. When the effect of fractures is emphasized, difference between minimum and maximum horizontal stresses increases, and consequently, occurs the major departure between the AVO signatures. As the effect of the fracture compliance is reduced, the rock tends to become isotropic, the minimum and maximum horizontal stress tend to be equal, thus the AVO signature departure becomes zero.

For cases where exist some influence of stress induced anisotropy (tectonic effects), yielding considerable differences between minimum and maximum horizontal stress, the anisotropic poroelastic stress model can include the called horizontal strain coefficients used commonly during 1D MEM processing like calibration factor. These coefficients are included in the stress model assuming a different solution with horizontal strains not constrained horizontally (not equal to zero), as shown by Blanton and Olsen (1999) and Gray et al. (2012).

It is recommended in cases of full stress induced anisotropy domain, to explore mathematical and physical theories that include a non-linear velocity to stress dependency models, e.g., Mavko et al. (1995).

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