Effect of Shale Anisotropy in Modification of In-situ Stress in Krishna-Godavari Basin, India

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Summary
This paper presents a stress analysis in an anisotropic medium in shallow bathymetry of Krishna-Godavari basin, India using finite element modeling. Thomsen anisotropic parameters (such as: ε, γ and δ) have been estimated from dipole shear sonic log using ANNIE model to obtain a better understanding of anisotropy. The dimensionless anisotropic parameters reveal vertical transverse isotropy for the Palakollu Shale and Raghavapuram Shale in the study area. Stress modelling using finite element method is carried out in 2D post stack seismic section using conventional well log data. The stress orientation clearly responds to changes in the anisotropic rock properties of Palakollu Shale, Tirupati Sandstone and Raghavapuram Shale formations. The contrasts of Young’s modulus (1.52 to 2.55) along with contrasts of stress magnitude (1.72 to 2.28) between layers are the major factor to rotate stress trajectories. Orientation of the maximum horizontal stress mostly varies from 40°N in Palakollu Shale to 17°N in Tirupati Sandstone to 20°N in Raghavapuram Shale. The model predicted stress orientation in Raghavapuram Shale matches with the orientation of derived breakout stress orientation of N20°E. The model predicted stress orientation in Raghavapuram Shale mostly follows the regional stress direction of this basin.

Introduction
The study area falling under the Krishna-Godavari (K-G) basin at east coast of India contains sediments of Godavari Clay (GC), Palakollu Shale (PS), Tirupati Sandstone (TS) and Raghavapuram Shale (RS) formations of Pliocene to Cretaceous age. PS characterises high gamma and low resistivity value whereas high gamma and high resistivity shale exists in the RS formation. The sandstones present in these formations tend to be thin and interbedded with shale showing the high seismic reflectivity at the sand-shale boundaries. Structural anisotropy occurs due to presence of faults, sedimentary bedding planes and aligned platy shaped clay minerals or grains (Bones and Zoback, 2006). The clay minerals in the matrix of shale exhibit textural anisotropy/ intrinsic anisotropy. The clay content variation and other minerals develop laminations or thin layering in shale. Fine horizontal layering i.e. the thickness of layers is less than the seismic wavelength results in vertical transverse isotropy (VTI). VTI also known as polar anisotropy can be quantified in the manner of including transverse isotropic planes with vertical axis of rotational symmetry. A VTI medium can be well characterized by having five independent elastic stiffness coefficients. Anisotropic shales are heterogeneous containing cracks, pores, joints, and especially bedding (Wang et al., 2017). These pre-existing discontinuities take part in progressive rock failure. Several researchers have carried out experiments indicating development of local tensile stresses under external compressive loads. This in turn causes initiation, propagation and interaction of micro cracks and finally rock failure (Wang et al., 2017). There are case studies on interpretation of image logs, seismic data and numerical modeling for analyzing stress magnitudes and stress orientation in sedimentary basins (e.g. Chatterjee and Mukhopadhaya, 2002; Chatterjee, 2008; Das and Chatterjee, 2017).

In this paper we investigate the stress orientation in an anisotropic shale medium for normal-faulted regime of K-G basin. Here we focus on investigating the analysis of Thomson anisotropic parameters from well log data and the stress pattern considering structural anisotropy in shale formation. This study will demonstrate the change of stress pattern of shale medium due to application of regional maximum lateral stress (S_H) pertaining to 1.85 km long seismic section-X of the shallow offshore parts of this basin.
Anisotropy in Raghavapuram Shale

The differences in properties of rock such as: density (ρ), Poisson’s ratio (v) and Young’s modulus (E) will play a role for modifying the existing stress vector. The contrast of rock properties is assumed to be due to inherent anisotropic nature of shale lithology and layered sediments under the study area.

Theory

Kaarsberg (1959) has evaluated anisotropy through ultrasonic P-wave and S-wave velocity measurements in shale (Kaarsberg, 1959). The shale anisotropy has the linkage between the textures of shale and the clay mineral alignment. Transversely isotropic (TI) nature of shale causes its rotational symmetry about vertical or horizontal axis. In this paper, symmetry axis is considered aligning with the vertical axis and the shale medium is known as VTI medium. Anisotropy is determined by comparison of vertical to horizontal wave speeds (Meléndez-Martínez and Schmitt, 2016).

In anisotropic medium the velocities of elastic wave change due to the propagation and polarization of particle. According to Hooke’s law, a complete characterization of an anisotropic rock requires twenty-one independent stiffness constants. TI medium serves as the most common anisotropic model, demanding five independent elastic parameters to complete rock characterization (Sil, 2013; Gholami et al., 2015). Hooke’s law for VTI medium is described in equation (1) by five independent stiffnesses.

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{yx} \\
\tau_{xz}
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\
C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{66} & 0
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{yx} \\
\gamma_{xz}
\end{bmatrix}
\]

\[\text{Equation (1)}\]

In the above equation, \(\varepsilon_i, \gamma_{ij}\) = normal and shear strains, respectively (i, j =x, y, z); \(\sigma_i, \tau_{ij}\) = effective normal and shear stresses, respectively where i and j corresponds to x, y and z direction. The five independent stiffness coefficients \(C_{11}, C_{13}, C_{33}, C_{44}\) and \(C_{66}\) for a VTI medium has given by,

\[C_{11} = C_{22}\]
\[C_{12} = C_{21}\]
\[C_{13} = C_{23} = C_{32} = C_{31}\]

\[C_{44} = C_{55}\]
\[C_{66} = \frac{C_{11} - C_{12}}{2}\]

The stiffness coefficients for TI media can be determined from wave speed measurements of core sample in the laboratory set up (Meléndez-Martínez and Schmitt, 2016)

\[C_{11} = \rho V_{p_{90}}^2\]
\[C_{33} = \rho V_{p_0}^2\]
\[C_{44} = \rho V_{SH_{90}}^2\]
\[C_{66} = \rho V_{SH_{90}}^2\]

\[C_{13} = \left(\frac{(4\rho V_{p_45}^2 - C_{11} - C_{33} - 2C_{44})^2 - (C_{11} - C_{33})^2}{4C_{44}}\right) - C_{44}\]

Where \(V_{p_{90}}, V_{p_0}\) and \(V_{p_{45}}\) are the compressional wave velocity polarized along orthogonal to the axis of symmetry, along the axis of symmetry and 45º to the axis of symmetry respectively. \(V_{SH_{90}}\) and \(V_{p_90}\) are the shear wave velocity polarised along the axis of symmetry and perpendicular to the axis of symmetry respectively.

Obtaining a better understanding of anisotropy in the VTI medium, Thomsen (1986) has proposed the three anisotropic parameters (such as: \(\varepsilon, \gamma\) and \(\delta\)) considering elastic stiffness coefficients. Thomsen anisotropy parameters for a TI medium can exactly be illustrated through the vertical propagating compressional and shear wave velocities along the axis of rotational symmetry (z) and three dimensionless anisotropic parameters defined as equations: 2, 3 and 4 are adopted from Meléndez-Martínez and Schmitt (2016):

\[\varepsilon = \frac{C_{33}-C_{44}}{2C_{44}}\]
\[\gamma = \frac{C_{66}-C_{44}}{2C_{44}}\]
\[\delta = \frac{(C_{13} + C_{44})^2 - (C_{33} - C_{44})^2}{2C_{44}}\]

For vertical well (drilled perpendicular to the bedding plane), only three of these five independent moduli \((C_{33}, C_{44}\) and \(C_{66}\) could be measured by dipole shear sonic imager (DSI) log. Due to non-availability of core samples, ANNIE model proposed by Shoenberg et. al. (1996) has been implemented to estimate the other stiffness coefficients: \(C_{11}\) and \(C_{13}\) (Shoeberg et.al., 1996). According to Schoenberg et al. (1996), the parameter \(\delta\), linking with the variation of vertical velocity in an anisotropic medium, is close to zero in the most sedimentary rocks. The constant \(C_{11}\) and \(C_{13}\) are given below:
Anisotropy in Raghavapuram Shale

\begin{align*}
C_{11} - C_{33} &= 2(C_{44} - C_{66}) \quad \text{---------------- (5)} \\
C_{13} + 2C_{44} - C_{22} &= 0 \quad \text{---------------- (6)}
\end{align*}

P-wave anisotropy is quantified by the Thomsen parameter \( \varepsilon \) and the difference between the horizontal and vertical polarized S-wave provides the second Thomsen anisotropy parameter \( \gamma \). In isotropic medium, these two anisotropic parameters will close to zero. The P-wave anisotropy parameter, \( \varepsilon \) lies in the range \(-0.375 < \varepsilon < 0.5\) indicating thin layered sediments having limited positive and mostly negative values. Rock with negative \( \gamma \) value signifies faster shear velocity in vertical direction than the shear velocity in horizontal direction (Berryman et al., 1999).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Displays well log responses of dynamic vertical and horizontal Poisson’s ratio (\( \nu_{\text{dyn}} \)), dynamic vertical and horizontal Young’s modulus (\( Y_{\text{dyn}} \)), static vertical and horizontal Young’s modulus (\( E_{\text{stat}} \)) for selected depth interval 410-1477m. Log derived parameters: degree of anisotropy (i.e. ratio between horizontal and vertical E) and Thomsen parameters such as: \( \varepsilon \), \( \gamma \) and \( \delta \) have been plotted.}
\end{figure}

**Model Setup**

The 1.85 km long seismic section-X passing through well W-1 displays the geological horizons with their ages (Figure 2a). This section illustrates the time and depth of the well indicating the top of formations. The seismic section-X shows the Godavari clay at the top of the section following Palakollu Shale, Tirupati Sandstone and Raghavapuram Shale up to the basement. The top of the basement is clearly marked by a prominent reflector. Palaeocene top has been observed at 230ms in the Palakollu Shale. The seismic section-X displays top of RS, top of Cretaceous within TS and basement of Permian age at 750ms, 500ms and 1580ms respectively (Das et al., 2017). Depending on the lithology studied from the well log and seismic data, the sedimentary column from 0.1 to 1.7 km is partitioned into 7 layers (Figure 2b). The elastic static rock properties for the 7 layers are listed in Table 1. In reference to Figure 3a, the model geometry (Figure 2b) is divided into six sedimentary strata of 1.85 km length. Layer 1 and 2 is composed of Godavari Clay and Palakollu Shale of Pliocene and Palaeocene age respectively. Layer 3 contains sediments of Tirupati Sandstone. The Raghavapuram Shale formation of Cretaceous age is divided into three layers namely; 4, 5 and 6. Basement is designated as layer 7. There is a variation of both of these elastic parameters: \( E \) and \( \nu \) in vertical as well as horizontal directions except layers 1 and 7.

The geometry of numerical model is built up with different elastic properties of rock (Table 1 and Figure 2). Top of the model is laterally constrained. Maximum regional horizontal stress (\( S_{\text{H}} \)) equaling 92\% of vertical stress for normal fault regime is applied to the left and right boundaries of the N-S section corresponding to 0.1 to 1.7 km depth (Figure 3b) (Chatterjee, 2008; Das and Chatterjee, 2017; Singha and Chatterjee, 2015). The vertical stress is estimated by cumulative sum of the formation density from the surface to the depth of interest (Das and Chatterjee, 2017). Formation density is obtained from density log. Overburden stress or vertical stress can be calculated using the following equation (7),

\[ \text{Vertical stress} = \int_{0}^{z} \rho(z)gdz \quad \text{---------------- (7)} \]

Where, \( z \) is the depth at point of measurement, \( \rho(z) \) is the bulk density of the rock at particular depth and \( g \) is the acceleration due to gravity. Vertical stress gradient in K-G basin is referred as 22.8 MPa/km (Singha and Chatterjee, 2015).

Investigations are confined to the Godavari Clay of Pliocene age (0.1-0.25 km), Palakollu Shale of Palaeocene age (0.25 to 0.50km), Tirupati Sandstone of Cretaceous age (0.50 to 0.78km), Raghavapuram Shale of Cretaceous age (0.78 to 1.60 km) and basement (1.60 to 1.70 km). The numerical values of \( \nu \) and \( E \) are computed using well log data for layers 2, 3, 4, 5 and 6 at the available depth interval 410-
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1477m. For layers 1 and 3 the quantitative value for rock properties has been adopted from Chatterjee and Mukhopadhyay, 2002. Errors are generally observed at the model peripheries due to constraints and boundary conditions. Hence, stress analysis will be focused at the central part of the modeled area.

Table 1: Elastic Rock Properties Employed in the 2-D FEM for section X of the K-G Basin for anisotropic media

<table>
<thead>
<tr>
<th>Layer</th>
<th>Horizontal Static Young’s modulus (MPa)</th>
<th>Vertical Static Young’s modulus (MPa)</th>
<th>Horizontal Poisson’s ratio</th>
<th>Vertical Poisson’s ratio</th>
<th>Average Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1290</td>
<td>1290</td>
<td>0.40</td>
<td>0.40</td>
<td>2100</td>
</tr>
<tr>
<td>2</td>
<td>1890</td>
<td>1598</td>
<td>0.33</td>
<td>0.38</td>
<td>2100</td>
</tr>
<tr>
<td>3</td>
<td>4650</td>
<td>4220</td>
<td>0.33</td>
<td>0.37</td>
<td>2240</td>
</tr>
<tr>
<td>4</td>
<td>7550</td>
<td>6050</td>
<td>0.28</td>
<td>0.34</td>
<td>2500</td>
</tr>
<tr>
<td>5</td>
<td>6894</td>
<td>5580</td>
<td>0.28</td>
<td>0.33</td>
<td>2300</td>
</tr>
<tr>
<td>6</td>
<td>4470</td>
<td>3530</td>
<td>0.26</td>
<td>0.31</td>
<td>2430</td>
</tr>
<tr>
<td>7</td>
<td>7230</td>
<td>7230</td>
<td>0.25</td>
<td>0.25</td>
<td>2450</td>
</tr>
</tbody>
</table>

The average $S_H$ values which acting at the right and left boundaries are: 3.25 MPa (0.1 to 0.25 km, layer 1), 7.87 MPa (0.25 to 0.50 km, layer 2), 13.42 MPa (0.50 to 0.78 km, layer 3), 18.04 MPa (0.78 to 0.94 km, layer 4), 24.01 MPa (0.94 to 1.35 km, layer 5), 30.94 MPa (1.35 to 1.60 km, layer 6) and 33.86 MPa (1.60 to 1.70 km, layer 7).

Finite Element Model (FEM)

Stress analysis has been carried out using finite element modelling using ANSYS FEM software. The model is meshed by six-noded 9844 numbers of triangular elements consisting of 19672 nodes. The smallest element size is 2sq.m. The equivalent stress: von Mises stress ($S_{VM}$) as implemented for 2D case is expressed as (Chandrupatla and Belegendu, 2014)

$$S_{VM} = \sqrt{S_1^2 + S_2^2 - S_1 S_2} \quad (8)$$

Where $S_1$ and $S_2$ are the principal stresses.

The focus of this modelling approach is examining the stress contour pattern at the layer interfaces as well as within sedimentary strata due to anisotropy. The discontinuities of elastic properties of rock at the edges of seven layers produce deformation due to application of $S_H$ at model boundaries (Figure 3).

Results

The model is mostly deformed at the boundaries subject to the application horizontal stress ($S_H$) magnitude. The explanations of the results are considered at the middle part of the model where deformation is minimum. The variation of stress
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trajectories due to contrast in material properties with the application of far field horizontal stress indicate the local stress modification under the study area. The stress orientation obtained from model has been validated with the stress orientation derived from breakout orientation. Formation Micro Imager (FMI) log data for a well is being used for estimation of recent time SH from breakout data.

The equivalent stress (SVM) is computed from maximum and minimum principal stresses and portrayed for anisotropic horizontal sedimentary layers in Figure 3. The magnitude of SVM varies from 1.25 at top to 37.31 MPa at the bottom of the model. The SVM is reached maximum at the basement. There is a variation of stress magnitude vertically and laterally. The SVM magnitude varies 1.25-4.32 MPa in layer 1, 2.27-4.83 MPa in layer 2, 7.87-11.04 MPa in layer 3, 17.43-19.05 MPa in layer 4, 18.32-26.79 MPa in layer 5, 18.60-23.24 MPa in layer 6 and 34.70-37.31 MPa in layer 7 respectively. The stress magnitude is showing maximum variation in layer 5 and minimum variation of layer 2. The magnitude of SVM has attained its maximum value compared to the overlying layers. The minimum contrast of 0.64 of average E is observed between layers 5 and 6 whereas maximum contrast attained at 2.55 between layers 2 and 3. The equivalent stress magnitude in the Palakollu Shale in layer 2 ranges from 2.27 to 4.83 MPa, for Tirupati Sandstone in layer 3 ranges from 7.87-11.04 MPa and for Raghavapuram Shale in layers 4, 5 and 6 varies from 17.43 to 26.79 MPa.

These contrasts of E along with lateral and vertical variation of stress magnitude rotates stress vector within layers and layer interfaces (Figure 3). The stress orientation is modified due to consideration of degree of anisotropy. Degree of anisotropy is observed to vary 1.3 to 1.4 and contrast in SVM and degree of anisotropy. Degree of anisotropy in layer 4 is observed to vary 1.3 to 1.4 and contrast in E is reasonable amounting 1.43 between layer 3 and 4. The stress magnitude contrast between layers 3 and 4 is 1.96. These above factors cause the rotation of principal horizontal stress vector towards N10-20°E in layer 4. This orientation follows with minimum stress rotation of about 5° in layer 5. Degree of anisotropy is less varying from 0.8 to 1.2 in layer 6. The contrast in stress magnitude and E are noted to be less between layers 5 and 6. There is rotation of stress vector (3 to 8°) between layers 5 and 6. Layer 6 shows little variation of stress orientation compared to the stress orientation observed in overlying layers. It is also observed degree of anisotropy is more in the depth interval of 780m to 1477m belonging to the Raghavapuram Shale whereas degree of anisotropy in the depth interval 500-780m is seen to be less in Tirupati Sandstone. Less degree of anisotropy is associated with more γ value in Tirupati Sandstone (Figure 1).

The model predicted horizontal stress orientation is compared with current stress direction obtained from microresistivity FMI data. The breakout data from only available adjacent well near to well W-1 penetrated through the Raghavapuram Shale is shown in Figure 3e. The S_H orientation is orthogonal to breakout orientation and is directed towards N20°E in this formation (Singha and Chatterjee, 2015). Therefore, model predicted S_H orientation matches well with the breakout derived S_H orientation in Raghavapuram Shale. Modelling results indicate principal horizontal stress direction which fairly fits with the NNE movement of Indian continent.

Conclusions

This numerical modelling approach demonstrates the stress distribution in the anisotropic shale medium. Stress orientation is modified due to consideration of
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VTI shale medium. Gradients of stress magnitudes are noticed in $S_{VM}$ between layers 2 and 3 followed by layers 3 and 4 due to reasonable contrast in E. Due to insignificant change in values of E between layers 4 and 5 as well as between layers 5 and 6, no distinguishable stress gradients are marked. Stress vector is rotated at the edge between layers 2 and 3 as well as between layers 3 and 4. The contrast in rock properties and contrast in anisotropic parameters enhances the rotation of stress vectors especially in layers 3 and 4. The Thomsen parameter such as: $\gamma$ indicates positive larger variation and less degree of anisotropy in Tirupati Sandstone. There is a variation of stress magnitude and orientation in the anisotropic layers in vertically as well as laterally. Raghavapuram Shale has rotation of principal stress 7° to 20° considering layers 4, 5 and 6. The model predicted stress orientation is validated from breakout derived SH orientation (N20°E). The model predicted stress orientation in anisotropic shale medium substantially fits with the recent time stress direction of K-G basin.

References


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