# Application of orthogonal dipole shear wave in the research of formation stress

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**Abstract.** In the formation stress research, the formation may be regarded as the transversely isotropic medium. The main research is horizontal direction two stresses, namely maximum and minimum stress. The orthogonal dipole shear wave logging was gained, which made it convenient to calculate the stress. This article quotes the elastic modulus and the stress relations, which derived the transversely isotropic formation stresses formula. The formation fracture pressure and the borehole stability expression were gained based on the fracture pressure elementary theory. At the same time it has also calculated many parameters such as the elastic modulus, anisotropy coefficient and so on. The orthogonal dipole shear wave logging was analyzed, which indicated that there is no need to consider formation tectonic factor. When calculating maximum and minimum stress was same based on fast and slow shear wave velocity was same, which reflected the formation assumed the isotropic. When they have the difference, it is showed that the formation assumes the anisotropy. Commonly-used the isotropic medium is one kind of the transversely isotropic medium.

## 1. Introduction

The size, direction and law of distributing and evolving the history of the formation stress are main contents in the exploration and development of oil and gas field, whose research contributes to announcing the distribution law of the oil and gas, predicts the rich collecting area of gas and oil, and exerts a great influence in exploiting the oil and gas rationally. The research and the application of formation stress computation pattern originated as early as the 80's. At that time because the well logging series were imperfect, many advanced instruments were not promoted, it is difficult to obtain some important parameters or data. Thus, the formation stress computation pattern was established on the isotropic medium rationale. Orthogonal dipole shear wave was promoted, which made it convenient to calculate formation stress. This paper will quote the elastic modulus and stress relations, derive the transversely isotropic formation stress computation pattern, , and obtain formation fracture pressure, borehole stability etc, according to the fracture pressure basic theory. All these parameters are helpful to ensure safe drilling, prevent the formation fracture, protect oil layer, and improve petroleum production.

## 2. Orthogonal dipole shear wave log

### 2.1. Basic principle of dipole shear wave log

Dipole shear wave log tool was used the transmitter and receiver signal, it causes increase in well side the pressure, but causes reduce in lateral pressure. The longitudinal wave and shear wave were excited in the formation. The direction of particle vibration and well axle is vertical, and the direction of particle vibration and propagation is consistent. The operating frequency of transducer is very low, usually lower than 4k HZ.

Such frequency is helpful to excite flexural wave. Longitudinal wave and shear wave incidence formation directly, but there are flexural wave along the bore hole, it will be produced in the bore hole fluid "the dipole". The flexural wave was produced by flexural borehole. in low frequency, whose propagation at the same speed as shear wave, in high frequency, its propagation is slower than shear wave. Dipole shear wave log can record to flexural wave in slow formation.

In slow formation, the time of flexural wave is relatively short, Whose frequency concentrates on the low frequency range. Besides flexural wave, more high frequency longitudinal wave exists the beginning of the wave form. in such typical slow formation, which can pick up the velocity of shear wave.

### 2.2. Shear wave is split in the formation

To the anisotropic formation, their physics characteristics are different on all directions. The propagation velocity (slowness) and propagation direction of acoustic can show the these characteristics of the formation, in other words, in the anisotropic formation, the shear wave velocity usually demonstrated the anisotropy, a bunch of shear waves incidence to the anisotropic formation (fracture formation), the incident shear wave may split the particle to be parallel and to be vertical the vibration propagation direction, which moves towards in the fracture and by different propagation velocity, this kind of phenomenon called the shear wave splits. The particle parallel fracture moves towards the vibration wave, the parallel fracture of particle moves towards vibration. The shear wave propagate along the axial of the well, the shear wave propagate along the axial of the well is fast, the former is called fast shear wave, the latter is called slow shear wave.

### 2.3. Orthogonal dipole shear wave

The orthogonal dipole shear wave has two different directions, two transmitters have 90 angles each other.

## 3. Stress and strain relations formation stress computation pattern

### 3.1. The stress and elastic constants

Assume that rock is isotropic, to the rock of the quiet balance state, applying the theory of elastic constants and Poisson relationship:

$$v = \varepsilon_x / \varepsilon_z = \varepsilon_x / \varepsilon_y \qquad (1)$$

According to Hook's law, Young's modulus is:

$$E = S_x / \varepsilon_x = S_y / \varepsilon_y = S_z / \varepsilon_z \qquad (2)$$

The amount of strain in the horizontal x-direction can be divided three parts: $\varepsilon_1$ strain in vertical stress z through Poisson's relationship, $\varepsilon_2$ strain in the y-direction through Poisson's relationship, and $\varepsilon_3$ strain in x-direction stress and Hook's law:

$$\varepsilon_x = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \qquad (3)$$

$$\varepsilon_x = v\frac{S_z}{E} + v\frac{S_y}{E} - v\frac{S_x}{E}$$

For the balance state of isotropic medium, have the following relationship $S_x = S_y, \varepsilon_x = 0$, so

$$vS_z + vS_x = S_x \qquad (4)$$

$$S_x = \frac{v}{1-v} S_z$$

Use equation (4) to calculate formation stress. Use equation (4) to calculate the horizontal stress inaccurate to test multiply actually, which should be corrected. $vS_z + vS_x = S_x$

### 3.2. The stress and elastic parameter in the anisotropic rock

The anisotropic rock refers to the difference of physical characteristics in all directions. The stress and elastic parameters are different for each unite volume of rock, whether Poisson's ratios along x direction.

$$v_{xy} = \varepsilon_x / \varepsilon_y$$

（5）

$$v_{xz} = \varepsilon_x / \varepsilon_z$$

Similar has along the y direction and the z direction Poisson ratios, the Young's module is:

$$E_x = S_x / \varepsilon_x$$
$$E_y = S_y / \varepsilon_y$$
$$E_z = S_z / \varepsilon_z$$

（6）

Strain of x- direction:

$$\varepsilon_x = v_{xz} \frac{S_z}{E_z} + v_{xy} \frac{S_y}{E_y} - \frac{S_x}{E_x}$$

（7）

Strain of y- direction:

$$\varepsilon_y = v_{yz} \frac{S_z}{E_z} + v_{yx} \frac{S_x}{E_x} - \frac{S_y}{E_y}$$

（8）

Suppose formation is the transversely isotropic, the effect of pore fluid pressure must be considered. The formation stress can be calculated using longitudinal wave and shear wave. Overburden pressure was calculated according to the standard technology of calculating formation stress. The maximum and minimum expression:

$$S_x = \left( \frac{v_{yx} v_{xy} + v_{xy}}{1 - v_{xy} v_{yx}} \right) \frac{E_x}{E_z} \left( S_z - \alpha p_p \right) + \alpha p_p$$

（9）

$$S_y = \left( \frac{v_{yx} v_{xy} + v_{yx}}{1 - v_{xy} v_{yx}} \right) \frac{E_y}{E_z} \left( S_z - \alpha p_p \right) + \alpha p_p$$

（10）

Where $\alpha$   Biot's constant, $P_p$   pore fluid pressure S$_z$ overburden pressure.

## 4. The formation fracture pressure is calculated

When mud density oversized, the formation may be broken, the mud permeating formation, polluting oil layer, In order to protect the oil layer, the formation fracture pressure must be calculated. Choose reasonable mud density. The formation fracture pressure refers to the rock has received the stress exceed the rock stretch strength, namely $\sigma_\theta = -S_t (S_t$ stretch strength). When the mud column pressure $P_M$ increases, $\sigma_\theta$ changes slightly, when $P_M$ increases to the certain degree, $\sigma_\theta$ becomes the negative value, namely the rock receives the hoop stress. When the stretching strength is greater than the rock pressure, the formation begins to rupture. Cracks and well collapses begin to appear in the minimum value, $\sigma_\theta$. Namely $\theta = 0°$ or $\theta = 180°$, has:

$$\begin{aligned} \sigma_\theta &= (S_x + S_y) + 2(S_x - S_y) - P_M - aP_P \\ &= 3S_x - S_y - P_M - aP_p \end{aligned} \quad （11）$$

$\sigma_\theta = 0$, $P_M$ namely for mud loss. $\sigma_\theta = -S_t$ substitute equation (11), have the formation fracture pressure:

$$\begin{aligned} 3S_x - S_y - P_M - aP_P &= -S_t \\ P_f &= 3S_x - S_y - aP_P + S_t \end{aligned} \quad （12）$$

When mud column pressure $P_{M_2} > P_f$, the formation cracking.

## 5. Calculation of the pressure that the borehole wall collapses

The main reason of the borehole wall collapses is due to relatively low pressure of mud column, there is the pressure on the wall of rock. The pressure in the well wall exceeds the strength of rock itself. There is collapse in the brittle formation, the borehole enlarged, Considering that the plastic formation has a deformation of the hole can be reduced. The borehole wall collapse has something to do with the stress of the wall surrounding rock.

The rock shearing failure mainly was controlled by maximum and minimum horizontal stresses. It can be find from borehole wall strength state maximum and minimum horizontal stress. The essential reason for the instability of the hole is the difference between borehole wall rock hoop stress and the radial stress. when $\theta = 90^0$ and $\theta = 270^0$, $\cos 2\theta = -1$, $\sigma_\theta$ has maximum value, this time $\sigma_\theta - \theta_r$ has maximum value. When $\theta = 90^0$ and $\theta = 270^0$ is easiest to produce borehole collapse, the pressure expression:

$$P_m = \frac{(3S_x - S_y) - 2CK + aP_P(K^2 - 1)}{(K^2 + 1)}$$

$$K = ctg(45^0 - \frac{\phi}{2})$$

$$（13）$$

## 6. Determination the maximum and minimum security drilling mud density

The main reason for the instability of the borehole wall is that the pressure of the mud column exceeds the pressure of the rock. When mud column pressure in the borehole is slightly low , the brittle formation can produce collapse, the borehole can be enlarged, the holes are easily deformed in the plastic formation resulting in fewer holes. The higher the pressure of the mud column, The more susceptible the crack is to the formation. The looser the formation, the easier it is to infiltrate. Choosing a reasonable mud density can protect the oil layer and drilling. The mud density should be considered according to the formation fracture pressure and the collapse pressure. Maximum and minimum security drilling density computation expression:

$$P\min = \frac{(3S_x - S_y) - 2CK + aPp(K^2 - 1)}{(K^2 + 1)} \quad （14）$$

$$P\max = 3S_x - S_y - aP_P + S_t \quad （15）$$

$$K = ctg(45^0 - \frac{\phi}{2})$$

Where $\phi$ takes $30^0$ in the sandstone  C rock inherent shearing strength, unit M Pa  maximum

and minimum horizontal stress Respectively, unit M Pa. Pp is the current well depth pore pressure, unit M Pa.   tensile strength.

## 7. Prediction of the hydraulic fracturing height

The development of oil fields is to obtain as many oil and gas as economic value. Increase production by fracturing in areas of low porosity and low permeability. When the pressure of the pump is too small, the effect of hydraulic fracturing cannot be obtained. If the hydraulic fracturing pressure is too large, it will cause a flow channel in the adjacent water layer, which will affect the oil and gas production. Therefore, the characteristics of low porous and low permeable reservoirs must be analyzed.

In the process of hydraulic fracturing, the pressure of the hole is generally larger than the pressure of the formation, and the formation begins to fracture. Under normal circumstances, the pressure at which the formation begins to rupture is the minimum horizontal stress. The direction of the rupture generally extends the maximum direction along the horizontal pressure and the direction of the minimum pressure perpendicular to the horizontal direction. When $S_x$ and $S_y$ was smaller than the tensile strength, the stress anisotropic were bigger than the intensity anisotropic, then will be surveyed the closure stress along outside defined the minimum horizontal stress. When the pressures in both directions are equal, the fracture may face to face. The minimum horizontal pressure is used to predict the hydraulic fracturing height in low porosity and low permeability formation.

## 8. Summary

The research and application of formation was regarded as the formation the transversely isotr opic medium. The transversely isotropic formation stress was inferred from the stress and the strain relations. The maximum and the minimum horizontal stress were obtained based on the oretical calculation, but direct calculation formation fracture pressure, there is no need to consi der formation tectonic factor. It is vital to compute and predict fracture height bore and hole stability. But the elementary theory of commonly-used isotropic medium is one kind of transv ersely isotropic medium. When fast and slow shear wave velocity are equal or approaching in the orthogonal dipole shear wave logging, the formation was regarded as the isotropic medium.

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