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# Estimation of Horizontal Stresses and Stress Directions from Inversion of Leak-off Test Data-A Computer Approach

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***Abstract*** **- In-situ stresses play the most important role in borehole stability during drilling operation. Problems pose by Uncertainties in the measurement of stress during drilling are enormous in the petroleum industry. In this paper a handy computer tool for estimating the magnitude and direction of horizontal matrix stresses was developed. This tool is based on the inversion model and uses data from a Leak off Test (LOT) together with overburden stress, pore pressure and well orientation data.**

***Index Terms: Insitu Stress, Leak off data, extended leak off test, Density Logs.***

SYMBOLS and Notations

| | |
|---|---|
| VSPs | Vertical Seismic Profiles (VSPs |
| LOT | Leak off Test |
| LOP | Leak off Pressure |
| XLOT | extended leak off Test |
| $\rho$ | Average mass density |
| $\rho(h)$ . | Density as a function of vertical Depth |
| $\rho_w$ | Density of water |
| $z_w$ | Water depth |
| $P_{wf}$ | Bottom Hole Flowing Pressure |
| h | Depth |
| g | Acceleration due to gravity |

## I. INTRODUCTION

Accurate prediction of the in-situ stresses) is important in the petroleum industry. Knowledge of the in-situ stress has implications for not only drilling safety and well design but also the costs of extraction of hydrocarbons. It is generally accepted that hydraulic fracturing is the most accurate method to measure stress at deep hole [12]. The magnitude and direction of the horizontal in-situ stresses can be estimated from leak-off data using inversion method.

Hubbert and Willis (1957) provided the most important effort in the interpretation of hydraulic fracturing mechanism, by using the theory of elasticity to reach the conclusion that the direction of the induced hydraulic fracture and the pressures recorded during borehole pressurization are directly related to the principal in situ stresses, this followed the successful use of hydraulic fracture as stimulation technique in the 1940s. Hydraulic fracturing has now become one of the key methods for rock stress estimation as suggested by the International Society for Rock Mechanics (ISRM). Fairhurst was among the first to advocate the use of hydraulic fracturing for in situ stress determination.

Kirsch (1989) presented solutions from which the basic equations describing the stress distribution around a horizontal, vertical and inclined wellbore may be derived. It is generally believed that a fracture initiates when the maximum tensile stress induced at any point around the wellbore exceeds the tensile strength of the formation at that point. When this occurs, the resulting fracture on the wellbore wall will have an orientation that is perpendicular to the direction of the most tensile principal stress. The pressure of wellbore failure is given by equation 1.3. [10]

The technique for inverting results from a minimum of two leak off tests at different well inclinations and azimuths, gives an estimate of both horizontal stress (maximum and minimum) magnitudes and directions. However, the published technique suffers from the assumption that shear stresses are neglected. The magnitude and direction of the horizontal in-situ stresses can be estimated from leak-off data using inversion method. [12] The method makes use of the fracture equation which is derived from the Kirsch equations and stress transformation equation. But the original method was inaccurate, because it ignores shear stress, and proposed an improved method. However found that the improved inversion also contained large uncertainties, in part due to the inaccuracy of the LOTs and suggested the use of multiple techniques to determine the in situ stress.

The in situ stress state can be determined from multiple fracturing data and induced fractures from image logs. A solution can be obtained with a minimum of two data sets. However, using an inversion technique, a solution can be obtained with any number of Datasets, as the solution is over determined [7].

## 2. METHODS FOR DETERMINATION OF REQUIRED DATA

### *2.1 Vertical stress determination*

The vertical stress is assumed to be equal to the weight of the overburden and can be calculated using knowledge of the rock densities. The vertical stress is determined using this formula:

$$\sigma_v = \rho g h \qquad 1.0$$

If the density varies with depth, the vertical stress is determined by integrating the densities of the overlaying rocks as shown in the equation below:

$$\sigma_v = \int_0^h \rho(h)\, g\, dh \qquad 1.1$$

In offshore area, water depth ($z_w$) is accounted for in the calculation of the vertical stress, that is;

$$\sigma_v = \rho_w g h_w + \int_{h_w}^{h} \rho_b(h)\, g\, dh \qquad 1.2$$

Density logs and check shot velocity surveys or vertical seismic profiles (VSPs) are the two main sources of density data.

*2.2 Minimum Horizontal Stress Magnitude*

Leak-off test (LOT), extended leak-off tests (XLOT) and minifracture tests can be used to constrain horizontal stress magnitudes. [16], [12]. The entire test involves increasing fluid pressure in the wellbore until a fracture is created at the wellbore wall. The LOT is the most commonly undertaken and the simplest of these tests. LOTs are conducted not for the purpose of making stress estimates, but in order to determine the maximum mud weight that can be used when drilling ahead. An XLOT is conducted when information on the stress tensor is of interest [18]. As the name suggests an XLOT is an extended version of LOT, using the same basic equipment, but a different test procedure. The third type of test discussed in this section is the minifracture or hydraulic fracture test, which is specifically designed to determine the horizontal stress magnitudes. LOTs can be used to estimate $\sigma_h$. XLOTs and minifracture test provide a more reliable estimate of $\sigma_h$ and under certain circumstances, an estimate of $\sigma_H$.

Leak-off pressure (LOP) is defined as the point on the pressure -time curve at which the pressure buildup deviate from linearity as illustrated in fig 1.0. This is interpreted as the fracture initiation pressure ($P_i$). The test is referred to as a formation integrity test (FIT) if no leak-off is observed, i.e. test is stopped at pre-determined pressure that does not generate a fracture.

To calculate the fracture pressure using data from wellbore fracture, the following equation will be applied [17]:

$$P_{wf} = 3\sigma_y - \sigma_x - P_0 + \sigma_{tensile} \qquad 1.3$$

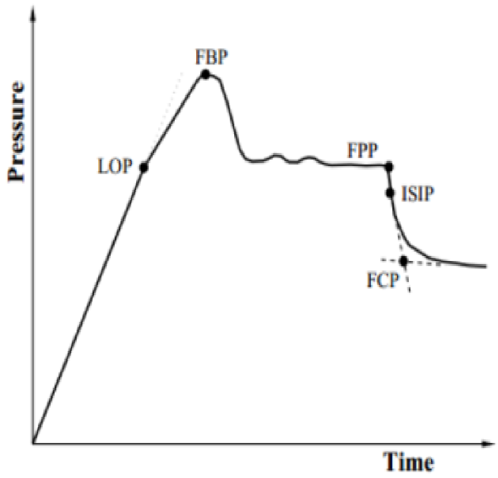


Fig 1.0 XLOT pressure versus time showing; LOP , FBP, FPP

XLOT and minifracture tests are conducted specifically for the purpose of stress determination [16]. These tests involves multiple cycles of pressurisation and de-pressurisation, but use different equipment. An XLOT can be conducted in place of a LOT during drilling when better quality stress information is required,[18].

Extended leak-off test apart from the fact that it a method for measuring $\sigma_h$ they can also be used to estimate $\sigma_H$ .

$\sigma_H$ can be determined from these tests using fracture initiation and/or reopening pressure (Hubbert and willis, 1957; Haimson and Fairhurst, 1967). The fracture initiation and/or reopening pressure depend on the stress concentration around an open hole. The minimum stress concentration around the wellbore is given by:

$$\sigma_{\theta\theta min} = 3\sigma_h - \sigma_H - P_w - P_p \qquad 1.4$$

Tensile failure occurs when the concentration exceeds the tensile strength of the rock (in an absolute sense, tensile stresses have been defined as negative). Hence for tensile failure of the wellbore wall:

$$\sigma_{\theta\theta min} = 3\sigma_h - \sigma_H - P_w - P_p \leq T \qquad 1.5$$

The fracture initiation pressure ($P_i$, LOP) is $P_w$ at fracture initiation, hence:

$$3\sigma_h - \sigma_H - P_w - P_p = T \qquad 1.6$$

The fracture initiation pressure can be read directly from the pressure record, as can $\sigma_h$ which is the fracture closure pressure (Fig 1.0). Hence eqn 1.6 can be rewritten as:

$$\sigma_H = 3P_c - P_i - P_p - T \qquad 1.7$$

Since the initial fracturing cycle overcomes overcomes tensile rock strength, for subsequent cycles equation 1.7 can be rewritten as

$$\sigma_H = 3P_c - P_r - P_p \qquad 1.8$$

### *2.2.1 Method of Breckels and van Eekelen (1982)*

The fracture gradients and *lower* bounds to LOPs for the US Gulf Coast is derived using the k value (ratio of horizontal to vertical effective stress) to define the relationships of how stress changes with depth. Differences only really occur in the way they determine the minimum effective stress. Following this historical review, a relationship between the minimum stress (Sh) and depth for the US Gulf Coast using fracture or "instantaneous shut-in" pressure data was derived, using a data set of over 300 points from the US Gulf Coast, they mathematically fitted a curve that described the lower bound to 93% of the data [13]. The curve, a combination of a linear and power-law relationship, meant the magnitude of Sh could be determined solely from the depth (D):

*S h* = 0.0197 Du45 for D<7500 feet. 1.9

*Sh* = 1.167 *D*- 4596 for D>7500feet. 1.10

More complex relationships were derived for Sh in abnormally pressured formations in the US Gulf Coast region using the depth and the magnitude of under/over-pressure (actual minus normal pore pressure). Data from Venezuela and Brunei were also used to derive power-law relationships for minimum stress determination using a combination of depth and under/over-pressure magnitude.

### *2.2.2 Method of Djurhuus and Aadnoy*

The theory for determining the in situ stress state from multiple fracturing data and induced fractures from image logs is given below. The position of the fracture on the borehole wall was determined by minimization of the tangential stress $\sigma_\theta$ [7], resulting in the equation

$$\tan(2\theta) = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \qquad 1.11$$

Thus the fracturing position on the borehole wall calculated from Equation (1.11) will be either $\theta = 0$ or $\theta$ =90.

At tensile failure (assuming rock tensile strength is zero)

when $\theta = 0$, and $\sigma_x > \sigma_y$

$$P_{wf} = 3\sigma_y - \sigma_x - P_0 + T \qquad 1.12$$

and when $\theta = 0$, and $\sigma_x < \sigma_y$

$$P_{wf} = 3\sigma_x - \sigma_y - P_0 + T \qquad 1.13$$

After substitution of the stress transformation equations, the above equations take the form

$$\frac{P_{wf}+P_0-\sigma_{tensile}}{\sigma_v} + sin^2\gamma = \{3sin^2\varphi - cos^2\varphi cos^2\gamma\}\frac{\sigma_H}{\sigma_v} + \{3cos^2\varphi - sin^2\varphi cos^2\gamma\}\frac{\sigma_h}{\sigma_v} \qquad 1.14$$

$$\frac{P_{wf}+P_0-\sigma_{tensile}}{\sigma_v} - 3sin^2\gamma = \{3cos^2\varphi cos^2\gamma - sin^2\varphi\}\frac{\sigma_H}{\sigma_v} + \{3sin^2\varphi cos^2\gamma - cos^2\varphi\}\frac{\sigma_h}{\sigma_v} \qquad 1.15$$

Redefining equation (1.14) and (1.15) results to:

$$P' = a\frac{\sigma_H}{\sigma_v} + b\frac{\sigma_h}{\sigma_v} \qquad 1.16$$

and in combination with a number of data sets, the two unknown horizontal in situ stresses sH and sh were determined from Eq. (1.16) using the least square method. [19] used a similar approach, but shear stress was included. Provided sH and sh have been obtained, further determined $\gamma$ and $\varphi$ from Equations. (1.11) but the back-figured values of $\gamma$ and $\varphi$ were not the same as the originally assumed values [30],[12] .

## 3 PROPOSED METHOD

In this section the method of inversion is used for estimating the magnitude of the minimum and maximum horizontal stresses and their directions. The input data for this method includes: pore pressure, overburden pressure, azimuth and inclination and data obtained from Leak-off, tests from different wells. The data are obtained from the already drilled wells and back calculation is done to determine the horizontal stress magnitudes of the field formation. As mentioned in the previous section this method is primarily based on the Kirsch's wellbore failure equation given. The fracture equation is in reference to an arbitrarily chosen borehole coordinate system x, y and z and therefore, it is applicable to any wellbore orientation.

A critical look at equationn 1.16 reveals that the only unknown terms are $\sigma_H$ and $\sigma_h$. Inserting the well geometry constants azimuth, and inclination, the square terms are resolved and the equations become linear. The linearized equations can be placed in a matrix form and be solved. When many datasets are available from different leak-off tests, the equations can be represented in the following simple form:

$$[P'] = [A][\sigma] \qquad 1.17$$

Though, equation 1.17 can be solved with as many datasets as available, a minimum of two datasets are required. The more the datasets used, the better the results obtained. When many datasets are used to solve for only the two unknowns, the equation would result in an over-determined system of linear equations. An exact solution cannot be obtained from the resolution of the over-determined system. The error which is the difference between the measured data and the solutions obtained from the computer model built in this paper is given by:

$$[e] = [A][\sigma] - [P'] \qquad 1.18$$

The error obtained from the above equation is squared using the least square method. The squared error is minimized by differentiating it with respect to $[\sigma]$ and equating the resultant equation to zero.

The maximum and minimum in-situ stresses can be calculated with the following equations:

$$[\sigma] = \{[A]^T[A]\}^{-1}[A]^T[P'] \quad 1.19$$

In order to solve the right hand side (RHS) of the above equation it is important to note that not all matrices are invertible but if a matrix is invertible then for a matrix A.

$$A^{-1}A = AA^{-1} = I \quad 1.20$$

It turns out that a naive approach to finding the inverse of a matrix for solving systems of linear equation is usually inefficient. In practice other techniques such as LUP decomposition will be more numerically stable. For the model presented in this paper the LU Decomposition method is used to obtain matrix inverse for solutions to the RHS of equation 1.19. The algorithm for the LU Decomposition is given below:

```
Initialize U = A, L = I
for k = 1 : m − 1
    for j = k + 1 : m
        L(j, k) = U(j, k)/U(k, k)
        U(j, k : m) = U(j, k : m) − L(j, k)U(k, k : m)
    end
end
```

## 4. RESULTS AND DISCUSSION

*Snorre field in the North Sea*

Three wells, P-7, P-8 and P-9 are considered for this test. The depths of the wells range from about 0.7 to 2.4 km and are presented in Table 1.0. Data sets from the table are inputted into the model to determine the in-situ stresses ad their directions. Stress values Obtained from the model are used to compute the fracture pressures used for validating the model. The process involves comparing the difference between results obtained from the model and the values from the measured data and selecting the set of results with the smallest error.

Table 4.1: Fractured data for Field case1

| Data set | Well | Casing (in) | Depth (m) | $P_{wf}$ $(s.g.)$ | $P_0$ $(s.g.)$ | $\sigma_v$ $(s.g.)$ | $\gamma$ (º) | $\varphi$ (º) |
|---|---|---|---|---|---|---|---|---|
| 1 | P-7 | $18\frac{5}{8}$ | 1160 | 1.44 | 0.9767 | 1.8481 | 19.37 | 196.92 |
| 2 | P-7 | $13\frac{3}{8}$ | 1774 | 1.71 | 1.3993 | 1.9649 | 70.63 | 195.90 |
| 3 | P-7 | $9\frac{5}{8}$ | 2369 | 1.87 | 1.3814 | 2.0511 | 60.56 | 220.76 |
| 4 | P-8 | $18\frac{5}{8}$ | 756 | 1.39 | 0.9483 | 1.7325 | 8.61 | 167.78 |
| 5 | P-8 | $13\frac{3}{8}$ | 1474 | 1.65 | 1.2213 | 1.9151 | 60.26 | 187.65 |
| 6 | P-8 | $9\frac{5}{8}$ | 2321 | 1.83 | 1.3789 | 2.0475 | 43.82 | 129.16 |
| 7 | P-9 | $18\frac{5}{8}$ | 1005 | 1.59 | 0.9685 | 1.8087 | 16.88 | 92.77 |
| 8 | P-9 | $13\frac{3}{8}$ | 1503 | 1.62 | 1.2568 | 1.9199 | 36.30 | 85.69 |
| 9 | P-9 | $9\frac{5}{8}$ | 2418 | 1.75 | 1.3840 | 2.0548 | 55.09 | 89.13 |

Figure 4.1 below shows the input interface for the computer model containing inputs for 2, 5 and 8 data sets. A simulation of all data sets (1,2,3,4,5,6,7,8,9) is run for all possible combinations around the wellbore (360 degrees) to determine state of stress, based on the minimum squared error. In validating results obtained using the above data sets by computing fracture pressure from the estimated stress value, The results from the model do not match the test data as indicated by large error values, this signify that the simulated datasets do not accurately represent the state of stress of the entire field depth. To get a better representation of the stress state of the field, simulations are done in smaller areas. For the sake of this study only three datasets (2,5,8) are used since for the three wells, these datasets occurs within the same hole section and as such provides a better representation for the state of stress in the formation.

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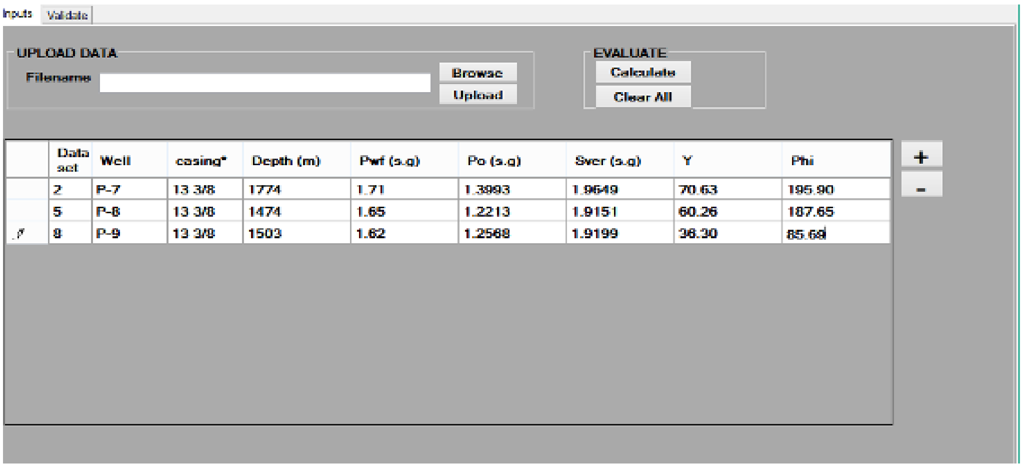


Figure 4.1 Input Interface for the computer model.

Running the model using the selected datasets for all possible combinations around the wellbore (360 degrees) to determine state of stress, based on the minimum squared error, the most suitable solution (i.e the solution with the smallest error using the least square method) is selected and given as:

$$\frac{\sigma_H}{\sigma_v} = 0.9213078$$

$$\frac{\sigma_H}{\sigma_v} = 0.59729985$$

$$\beta = 134^0$$

Squared error= 0.00005

The results given for the horizontal stresses ratio show that the maximum horizontal principal in-situ stress is 0.9213078 times the overburden, the minimum horizontal stress is 0.59729985 times the overburden and the angle beta gives the direction of the maximum in-situ stress with reference to the North. Figure 1.2 below shows the result interface for the computer model.

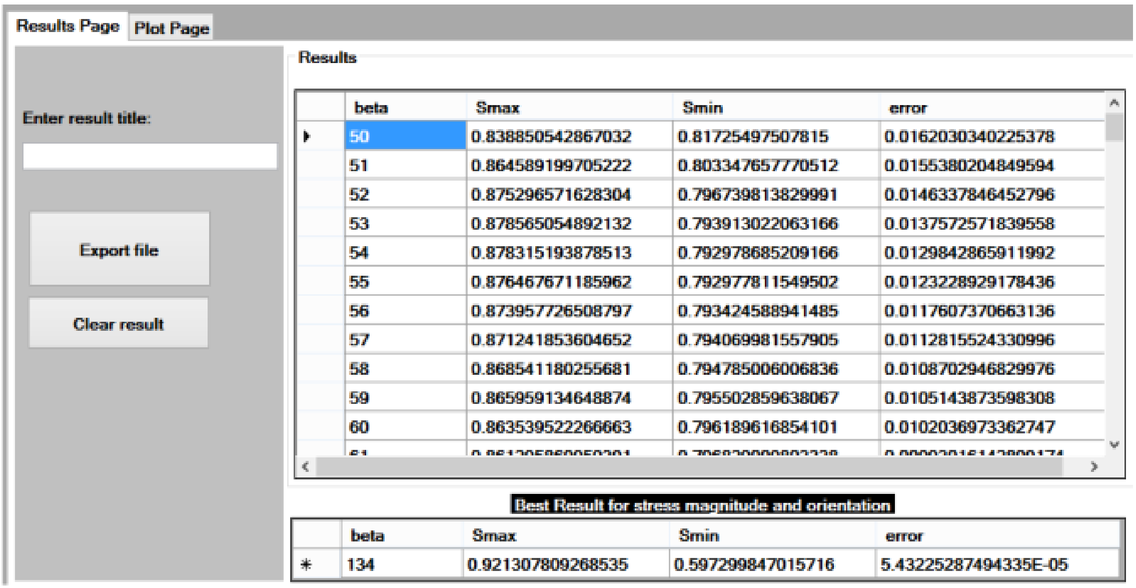


Figure 4.1: Result interface for the computer model

The interface above shows two separate tables. The first table displays the stress results and their corresponding directions for all possible combination around the wellbore (through 360 degrees). The second table shows the best match for the stress value and stress direction based on smallest squared error. Fig 1.3 below show the validation of this matched value relative to the other values obtained from the computer model.

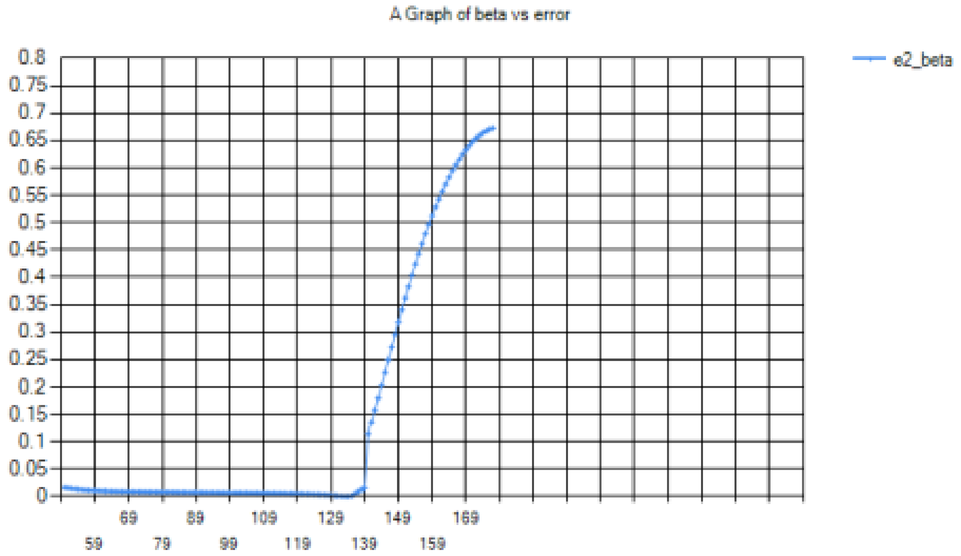


Figure 1.3: A plot of $\beta$ Versus Squared error wing direction of $\sigma_H$

Table 1.1 Results for selected Dataset run

| $\beta$ | $\frac{\sigma_H}{\sigma_v}$ | $\frac{\sigma_H}{\sigma_v}$ | Squared error |
|---|---|---|---|
| 50 | 0.838850542867032 | 0.81725497507815 | 0.0162030340225378 |
| 51 | 0.864589199705222 | 0.803347657770512 | 0.0155380204849594 |
| 52 | 0.875296571628304 | 0.796739813829991 | 0.0146337846452796 |
| 53 | 0.878565054892132 | 0.793913022063166 | 0.0137572571839558 |
| 54 | 0.878315193878513 | 0.792978685209166 | 0.0129842865911992 |
| 55 | 0.876467671185962 | 0.792977811549502 | 0.0123228929178436 |
| 56 | 0.873957726508797 | 0.793424588941485 | 0.0117607370663136 |
| 57 | 0.871241853604652 | 0.794069981557905 | 0.0112815524330996 |
| 58 | 0.868541180255681 | 0.794785006006836 | 0.0108702946829976 |
| 59 | 0.865959134648874 | 0.795502859638067 | 0.0105143873598308 |
| 60 | 0.863539522266663 | 0.796189616854101 | 0.0102036973362747 |
| 61 | 0.861295860959391 | 0.796829009803338 | 0.00993016142899174 |
| 62 | 0.859226503125309 | 0.797414328099249 | 0.00968737387762403 |
| 63 | 0.857322547062641 | 0.79794401505087 | 0.00947022720962884 |
| 64 | 0.855572003660176 | 0.798419233330325 | 0.00927462388895462 |
| 65 | 0.85396198033385 | 0.79884250447445 | 0.00909725229009785 |
| 66 | 0.852479799906464 | 0.799216945599564 | 0.00893541486832753 |
| 67 | 0.85111354270907 | 0.799545843607931 | 0.00878689677851594 |
| 68 | 0.849852276332249 | 0.799832422353013 | 0.00864986522865026 |
| 69 | 0.848686118176835 | 0.800079720860271 | 0.00852279201934713 |
| 70 | 0.847606211172081 | 0.800290535484637 | 0.00840439356238269 |
| 71 | 0.84660465728091 | 0.800467398573808 | 0.00829358411372414 |
| 72 | 0.845674433435153 | 0.800612577535167 | 0.00818943904559873 |
| 73 | 0.844809303283168 | 0.800728084814862 | 0.00809116579067924 |
| 74 | 0.844003731758339 | 0.800815693199392 | 0.00799808068773419 |
| 75 | 0.843252805874515 | 0.800876953172715 | 0.00790959039734615 |
| 76 | 0.842552163138437 | 0.800913210452232 | 0.00782517688053778 |
| 77 | 0.841897927864727 | 0.800925622660069 | 0.0077443851734731 |
| 78 | 0.841286655099705 | 0.800915174583674 | 0.00766681337042099 |
| 79 | 0.840715281581425 | 0.**800882691773**294 | 0.0075921043613033 |
| 80 | 0.840181083054676 | 0.800828852393633 | 0.00751993897125487 |
| 81 | 0.83968163724467 | 0.800754197340437 | 0.00745003022630603 |
| 82 | 0.839214791827676 | 0.800659138680038 | 0.00738211852780377 |
| 83 | 0.838778636795113 | 0.800543966488756 | 0.00731596756308459 |
| 84 | 0.838371480675102 | 0.800408854171129 | 0.00725136081456442 |
| 85 | 0.837991830144222 | 0.80025386232714 | 0.00718809855627019 |
| 86 | 0.83763837262804 | 0.80007894122405 | 0.00712599524776064 |
| 87 | 0.837309961550021 | 0.799883931909538 | 0.00706487725172119 |
| 88 | 0.837005603944095 | 0.799668565981487 | 0.00700458081431108 |
| 89 | 0.836724450196705 | 0.79943246400617 | 0.00694495025733587 |
| 90 | 0.83646578572999 | 0.799175132550901 | 0.00688583633912274 |
| 91 | 0.836229024479843 | 0.798895959769205 | 0.00682709474700112 |

| | | | |
|---|---|---|---|
| 92 | 0.836013704061767 | 0.798594209445437 | 0.00676858468887777 |
| 93 | 0.835819482554684 | 0.798269013371024 | 0.00671016755477996 |
| 94 | 0.835646136869239 | 0.797919361884581 | 0.00665170562159648 |
| 95 | 0.835493562703809 | 0.797544092362003 | 0.00659306077569828 |
| 96 | 0.835361776129654 | 0.797141875388294 | 0.00653409322873155 |
| 97 | 0.835250916887687 | 0.796711198277944 | 0.00647466020169253 |
| 98 | 0.835161253525106 | 0.796250345532636 | 0.00641461455139619 |
| 99 | 0.835093190552348 | 0.795757375729737 | 0.00635380331160033 |
| 100 | 0.835047277862053 | 0.795230094218146 | 0.00629206611825546 |
| 101 | 0.83502422272504 | 0.794666020853213 | 0.0062292334844844 |
| 102 | 0.835024904767503 | 0.794062351821639 | 0.00616512488576094 |
| 103 | 0.835050394443976 | 0.793415914380424 | 0.0060995466091054 |
| 104 | 0.835101975658534 | 0.792723113046474 | 0.0060322893115852 |
| 105 | 0.835181173361326 | 0.79197986540773 | 0.00596312522257964 |
| 106 | 0.835289787170359 | 0.791181525257383 | 0.00589180491050807 |
| 107 | 0.835429932355899 | 0.790322790146714 | 0.00581805351731003 |
| 108 | 0.835604089898374 | 0.789397589663598 | 0.00574156634185279 |
| 109 | 0.835815167820635 | 0.788398949710367 | 0.00566200362535858 |
| 110 | 0.836066576643381 | 0.787318826689764 | 0.00557898435618433 |
| 111 | 0.836362322677195 | 0.786147903690059 | 0.0054920788656535 |
| 112 | 0.83670712402852 | 0.784875338319548 | 0.0054007999283452 |
| 113 | 0.837106555778596 | 0.783488448533605 | 0.00530459200570599 |
| 114 | 0.837567232964318 | 0.781972318275688 | 0.00520281817666725 |
| 115 | 0.838097042997369 | 0.780309298511002 | 0.00509474417787819 |
| 116 | 0.838705443369512 | 0.778478370527241 | 0.00497951882344552 |
| 117 | 0.839403846454329 | 0.77645432611432 | 0.00485614988452616 |
| 118 | 0.840206121751503 | 0.774206701778474 | 0.00472347428085376 |
| 119 | 0.841129258280011 | 0.771698379031067 | 0.00458012117706646 |
| 120 | 0.842194247930774 | 0.768883726284504 | 0.00442446631836897 |
| 121 | 0.843427277403088 | 0.765706104304198 | 0.00425457577020172 |
| 122 | 0.844861356469777 | 0.762094477876667 | 0.0040681373589532 |
| 123 | 0.846538570842917 | 0.75795875841556 | 0.00386237904185886 |
| 124 | 0.848513239614404 | 0.753183326876016 | 0.00363397629762787 |
| 125 | 0.850856395693436 | 0.747617928633016 | 0.00337895801213026 |
| 126 | 0.853662212622996 | 0.741064766380329 | 0.00309263820241295 |
| 127 | 0.857057287812815 | 0.733260145655415 | 0.00276964328723255 |
| 128 | 0.861214031548835 | 0.723848585101269 | 0.00240420512141005 |
| 129 | 0.866369581544968 | 0.712347519698784 | 0.00199113148418028 |
| 130 | 0.8728507256524 | 0.698103939995059 | 0.00152845640144262 |
| 131 | 0.881099795176144 | 0.680258629529337 | 0.00102424023496015 |
| 132 | 0.891674180985399 | 0.657786267799832 | 0.000513625674200632 |
| 133 | 0.905112436616509 | 0.629857155605929 | 0.00010070937934591 |
| 134 | 0.921307809268535 | 0.597299847015716 | 0.0000543225287494335 |
| 135 | 0.93746237490722 | 0.567043341766276 | 0.000975141183573695 |
| 136 | 0.944005264611821 | 0.560232341455631 | 0.00380338075971586 |
| 137 | 0.925957509124309 | 0.607022115678056 | 0.00873056225409314 |
| 138 | 0.884557231475457 | 0.699874833335905 | 0.0135425697539379 |
| 139 | 0.843660303528262 | 0.786166581745686 | 0.0159311613582524 |
| 140 | 1.99515295954198 | 0.472106099551516 | 0.113949347874849 |
| 141 | 2.03542020245174 | 0.557852274364309 | 0.135142733589768 |
| 142 | 2.06990628066773 | 0.639079713153741 | 0.157152073123614 |
| 143 | 2.09870559804928 | 0.715499104787395 | 0.179759057591886 |
| 144 | 2.12196368028863 | 0.78691301180499 | 0.20276318652632 |
| 145 | 2.13986597183613 | 0.853205358940119 | 0.225982879872826 |
| 146 | 2.15262754249968 | 0.914330533443066 | 0.249255828836673 |
| 147 | 2.16048390646119 | 0.97030260390239 | 0.272438734761705 |
| 148 | 2.16368305168408 | 1.0211850350029 | 0.295406579241589 |
| 149 | 2.16247869537355 | 1.06708115829556 | 0.318051555468791 |
| 150 | 2.15712472069145 | 1.1081255587418 | 0.340281773562967 |
| 151 | 2.1478707090004 | 1.14447645551882 | 0.36201983375293 |
| 152 | 2.13495845736402 | 1.17630909306914 | 0.383201342604351 |
| 153 | 2.11861935925405 | 1.2038101129536 | 0.403773430166149 |
| 154 | 2.09907252455175 | 1.22717284627242 | 0.423693310627424 |
| 155 | 2.07652351933639 | 1.24659344753956 | 0.442926916127907 |
| 156 | 2.05116361514017 | 1.26226778128486 | 0.461447622774248 |
| 157 | 2.02316944869367 | 1.27438896993121 | 0.479235079536253 |
| 158 | 1.99270300572272 | 1.2831455136254 | 0.496274144287662 |
| 159 | 1.95991185494563 | 1.2887198980463 | 0.512553926529244 |
| 160 | 1.92492957044403 | 1.29128761349431 | 0.528066932995722 |
| 161 | 1.88787629164608 | 1.29101651682684 | 0.542808310127768 |
| 162 | 1.84885938006959 | 1.28806647635923 | 0.556775176041547 |

| | | | |
|---|---|---|---|
| 163 | 1.80797414065837 | 1.28258924823229 | 0.569966033942025 |
| 164 | 1.76530458303403 | 1.27472854065883 | 0.582380258729955 |
| 165 | 1.72092420436057 | 1.26462022972822 | 0.594017648707283 |
| 166 | 1.67489678089468 | 1.25239269698996 | 0.604878034683575 |

## 5. CONCLUSION

Wellbore instability problems which result to additional drilling cost are majorly due to matrix stress. Hence accurately predicting the in-situ stresses in a rock formation can go a long way to solve a lot of the challenges facing the petroleum and mining industries and a whole lot of money could be saved and accidents averted. In this project, a handy tool that is easy to use to predict the horizontal principal in-situ stresses was developed. The results from simulations obtained from this work demonstrated the reliability of this program to:

1. Estimate the magnitude of the horizontal principal matrix stresses of a rock field based on data obtained from LOT, pore pressures, overburden stresses and well directions. The model can accommodate any number of input data but a minimum of three input data is required to get a meaningful result.

2. The estimated magnitude of the matrix stresses can be used to calculate fracture pressures.

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