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Well Collapse Modelling And Application Of Two WorkFlows On Heidrun Field In Norwegian Sea

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ABSTRACT

Well instability problem has been and still is a critical issue in the oil industry. Prior to drilling, the primary step during planning phase is designing well pressure prognosis. An allowable safe operational window is bounded by well fracture and collapse pressures. This paper deals with the application of density log derived uniaxial compressive strength (UCS) used for collapse strength determination. The presented workflows are tested on Heidrun well program. The results are compared with sonic log derived methods. The results illustrate the potential application of the presented workflows.

1 INTRODUCTION

Well instability is a cost factor for the industry. Wellbore instability problems alone increase the overall drilling budget by about 10% (Aadnøy 2003) [1]. The main driving forces for well bore instability are mechanical (stress, pressure), thermal and chemical. The failure mechanisms are tensile and collapse (Bernt S. Aadnøy 2011) [2]. Several theoretical and experimental well stability studies have been done in the industry today. Despite the efforts and increased knowledge about the subject, the industry is still facing this problem in shales, unconsolidated and fractured formations.

In an appropriately designed drilling window, one can determine an optimized mud density, which can avoid a possible well instability problem. In order to delineate an operational safe window, the knowledge of in-situ stress, pore pressure and rock strength are also important. These parameters are used as an input for well collapse and well fracture models. There are several models documented in literature among others, Aadnøy and Chevert (1988) [3], and Fjær et al (1999) [4].

Generally, appropriate mud weight, chemistry and rheology properties of drilling fluids are the main parameters used for wellbore stability provided that the correct well pressure operational window is designed.

This paper presents the application of sonic and density derived uniaxial compressive strength (UCS), which is an input parameter for well collapse strength estimation.

2 WORKFLOW

In this paper, two workflows will be tested and compared. **Figure 1a** is workflow-1 that estimates USC from travel time(Compressional wave velocity) and considered as Reference. **Figure 1b** illustrates workflow 2, which estimmates UCS indirectly from density log. For workflow 2, we need to have an empirical model that estimates velocity from density log. These two workflows will be tested later on Heidrun field to verify their applicability.

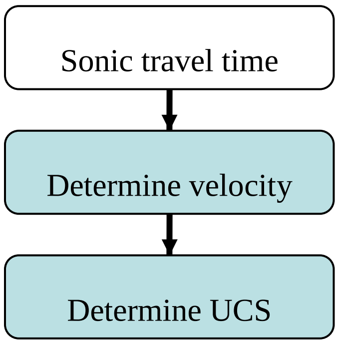

Figure 1a: Workflow-1(Referance)

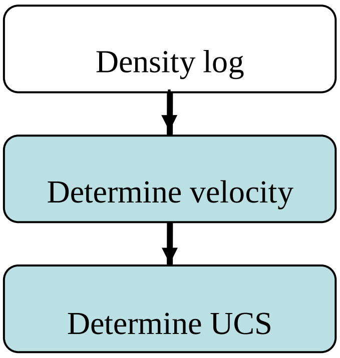

Figure 1b: Workflow-2(This paper work)

3 THEORY

3.1 Well Collapse Failure model

In literature, there are several rock collapse failure criteria. Mohr-Coulomb is the most commonly used shear failure criteria. The model is a function of formation pressure, uniaxial compressive strength, rock failure angle and in-situ stresses. Based on the near wellbore stress analysis, we have selected the Mohr–Coulomb well collapse model given as [5]

$$P_w \leq \frac{3\sigma_x - \sigma_y - C_o - \alpha_o P_p (1 - \tan^2 \beta)}{1 + \tan^2 \beta} \qquad 1$$

Where, σ_x is stress transformed in-situ stress, σ_y is stress transformed in-situ stress, σ_h is horizontal minimum in-situ stress, C_o is uniaxial compressive strength, P_p is Pore pressure, α_o is Biot coefficient, ν is Poisson ratio and β is failure angle.

3.2 In-situ Stresses

The undisturbed state of stress, which are exerted on the sediment are called the in-situ stresses. These are vertical stress due to the overburden weight of the sediments, and the two horizontal stresses, which are due to the overburden stress, the tectonics/lithological plate tectonics and geological depositions.

3.2.1 Horizontal Stresses

When an overburden stress exists in a formation, it will also push the sediment in the horizontal direction in additional to the vertical squeezing. This will result in horizontal stresses. Assuming that a rock as isotropic and tectonic effect is not considered, a simple model for horizontal in-situ stress is given as [4]:

$$\sigma_h = \frac{\upsilon}{1-\upsilon}(\sigma_v - \alpha_o P_p) + \alpha_o P_p \qquad 2$$

Where σ_h is the minimum horizontal in-situ stress, σ_v is overburden stress, P_p is pore pressure, α is Biot – coefficient.

For any well inclination and azimuth, the in-situ stress (σ_h) will be transformed by stress transformation equations provided in appendix B.

3.2.2 Vertical stress

Vertical stress in the sediments increases with the depth as more overburden will be exerted due to an increase number of sediments. The overburden stress at a particular depth (z) can be determined as [4].

$$\boldsymbol{\sigma_v = \int_0^D \rho(z) g dz} \qquad 3$$

ρ = density of the material, g is the acceleration of gravity, dz = thickness of the formation, σ_v = vertical stress.

3.3 Density (ρ) –Velocity (V_p) relation

3.3.1 Gardner's equation

Gardner's equation is an empirical density-velocity relation. The model is popular in the petroleum exploration. The equation reads [6]:

$$\rho = 0.23 V_p^{0.25} \qquad 4$$

Where the unit of V_p is feet/s and density is in g/cm^3.

3.3.2 New NCS based derived model

From several field data obtained from NCS, density and velocity model has been developed [7, 8, 9]. In this paper, we considered the best fit model derived from NCS data [10]:

$$\boldsymbol{\rho} = -4{,}931 * 10^{-9} * \boldsymbol{v_p^2} + 0{,}0001694 * \boldsymbol{v_p} + 1{,}127 \qquad 5$$

Where, the unit of Vp is ft/s and density is in g/cm^3.

Among other models, the applicability of Equation 5 along with Equation 4 will be tested on Heidrun field later.

3.4 Uniaxial compressive strength

Uniaxial compressive strength is the strength of the rock when the rock is compressed in the uniaxial direction, and indicates the maximum load carrying capacity of a rock specimen. Practically it is impossible to extract core and estimate the UCS of the formation. Among others, Horsrud (2001) [11] also derived a correlation equation that relates the uniaxial compressive strength with the sonic velocity. The model has been derived based on several shale obtained from North Sea Continental Shelf (NCS). The models is given as:

$$C_o\left[MPa\right] = 0.77 V_p^{\ 2.93} \tag{6}$$

Where, the unit of Vp is km/s.

4 APPLICATION OF WORKFLOWS ON HEIDRUN FIELD

Heidrun field is located the Haltenbanken area offshore Mid-Norway (see NPD FactMap, **Figure 2**) [12]. The field is located in a very environmentally susceptible area. Therefore, instead of oil based mud, inhibitive KCl Water based muds are used on the fields, which acts as reactive clay to drill wells on this field (Stjern, et al., 2003) [13]. **Figure 3** is the well program used to drill the well. The collapse pressure shown on the figure was calculated by using Stassi-d'Alia failure criterion. However, in this paper we used Mohr-Coulomb model given as Eq. 1and the results are compared.

As shown on the lithostratigraphic column of Heidrun, most of the drilling section contain shale. Therefore, for the simulation, typical shale rock properties were considered [Fjær et al. (2008][4]. Horsrud model's (Eq. 6) was used to estimate the UCS since the model suits for shale formation.

Here, we are going to look at the applicability of workflows presented in **Figure 1a** and **Figure 1b**. Workflow 1 is the commonly used approach, which uses the measured compressional wave velocity through sonic logging. This will be considered as reference with which the workflow 2 is to be compared with. Workflow 2 is the main focus of this paper. Workflow 2 is designed in case of no available compressional wave velocity due to for example tool failure in the area where we are going to drill. Considering these scenarios, according to workflow 2, we need to determine the compressional wave velocity from density-velocity model. The applicability of Workflow 2 will therefore depend on the correct density-velocity model.

As reviewed in the theory part, we considered two density-velocity models. The first one is the commonly used model as shown in Eq. 4. The second model (Eq. 5) is the newly derived model in this paper, which is based on several NCS data. Therefore, the main input parameter here is density log from which we determine velocity in order to compute the USC.

A well in Heidrun field was selected. From Figure 3, we discretized the pore pressure data every 100m. **Figure 4a** shows the comparison between the reference (sonic based) derived UCS and the Gardner velocity based USC result. Similarly, **Figure 4b** shows the comparison between the reference (sonic log based) UCS and the new NCS model based USC estimated result. As shown from these two plots, the UCS estimations are quite qood with certain degree of deviations from the sonic based result. These two profiles are an input parametes for well collapse pressure modelling.

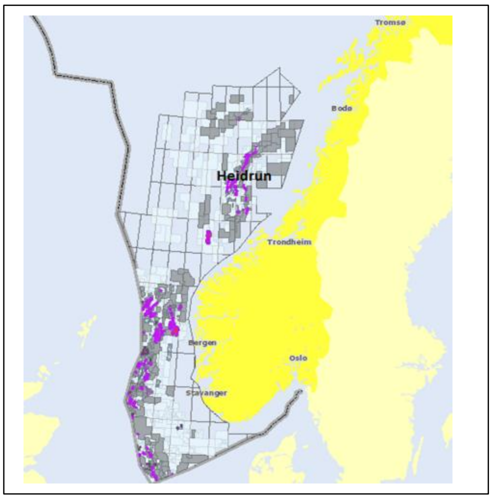

Figure 2: Location of Heidrun field (NPD FactMap)[12]

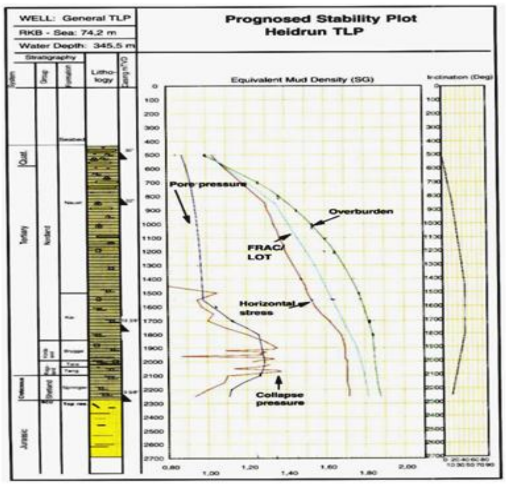

Figure 3: Prognosis stability plot for a typical Heidrun TLP well (Stjern, et al., 2003)

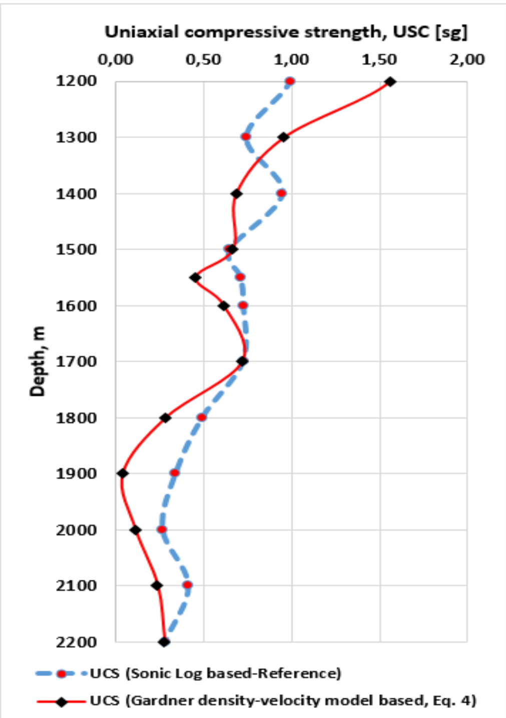

Figure 4a: UCS estimation of sonic based and Gardner ρ-V_P based model (Eq. 4)

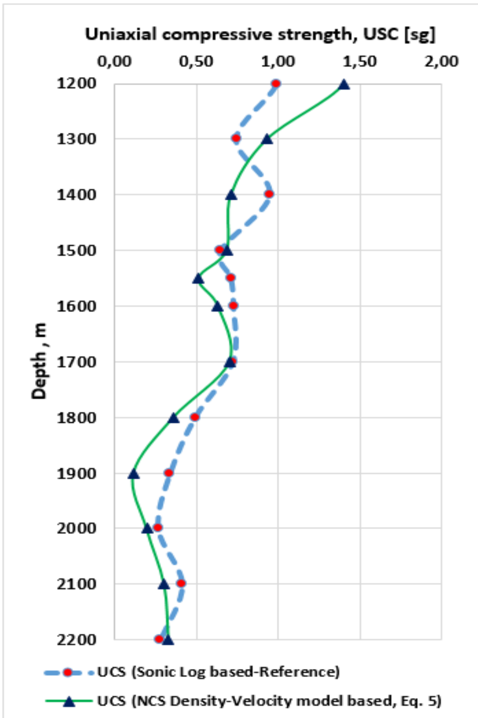

Figure 4b: UCS estimation of sonic based and new NCS density based model (Eq. 5)

Finally, using the UCS profiles, pore pressure and the transformed insitu stress, formation elastic properties, failure angle, the well collapse pressure prognosis was contructed and shown on **Figures 5a** and **Figure 5b**. The plots are based on the presented workflow 1 and work flow 2.

The workflow-1 result is compared with workflow 2 (i.e based on the Gardner and the new NCS density-velocity models) results. As shown, the results illustrate the applicability of the presented methods. In addition, one can also observe that the Mohr-Coulomb based well collapse prediction is somewhat similar trend to the Stassi-d'Alia failure criteria based result displayed on **Figure 3**.

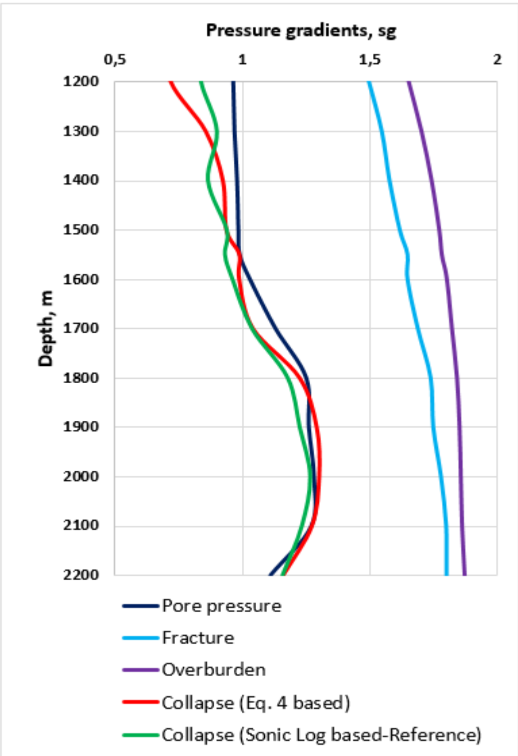

Figure 5a: Well collapse determination using workflow-1 [Sonic log-Reference] and Workflow-2 [Gardner density-veocity model (Eq. 4)]

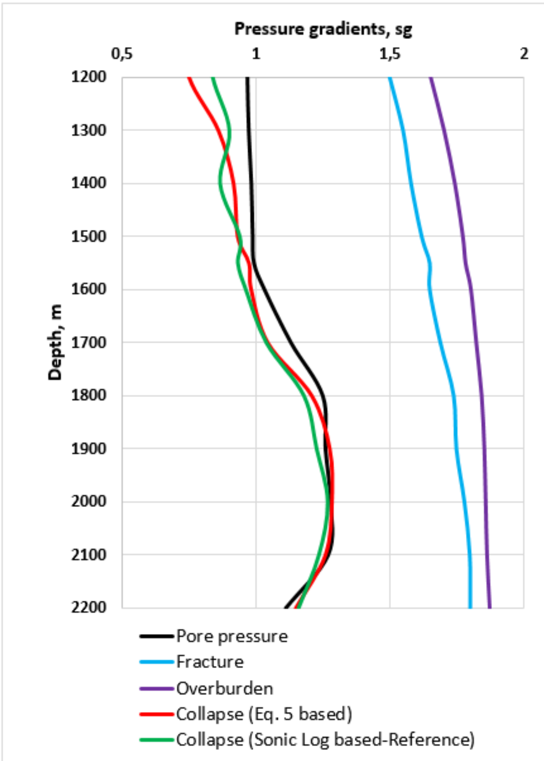

Figure 5a: Well collapse determination using Workflow-1 [Sonic log-Reference] and Workflow-2[New NCS based density-veocity model (Eq. 5)]

5 SUMMARY

Well instability problem has been a critical issue in the oil industry. In this paper two workflows are presented and analyzed on the Heidrun field. The two workflows are used to estimate the uniaixal compressive strength, one based on a sonic log and the second one derived indirectly based on density log. Both of these workflows require accurate log data and a good density-velociy model. Based on the presented analysis on the Heidrun field, the results illustrate the potential application of the presented workflow. However, more analysis needs to be peformed.

NOMENCLATURE

σ_x = stress transformed in-situ stress, psi/bar
σ_y = stress transformed in-situ stress, psi/bar
σ_h = horizontal minimum in-situ stress, psi/bar
C_o= Uniaxial compressive strength, psi/bar
P_p= Pore pressure, psi/bar
α_o= Biot coefficient, [-]
ν= Poissons ratio, [-]
β = failure angle, deg

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Appendix A: Stress concentration at wellbore

The stress concentration for any deviated well at the wall of a wellbore is given as [2]:

$$\sigma_r = P_w \quad \text{A1}$$

$$\sigma_\theta = (\sigma_x + \sigma_y - P_w) - 2(\sigma_x - \sigma_y)\cos 2\theta - 4\tau_{xy}\sin 2\theta \quad \text{A2}$$

$$\sigma_{zz} = \sigma_z - 2\upsilon(\sigma_x - \sigma_y)\cos 2\theta - 4\upsilon\tau_{xy}\sin 2\theta \quad \text{Axial stress, plain strain} \quad \text{A3}$$

$$\sigma_z = \sigma_{zz} \quad \text{Axial stress, plain stress} \quad \text{A4}$$

$$\tau_{r\theta} = \tau_{rz} = 0 \quad \text{A5}$$

$$\tau_{\theta z} = 2(-\tau_{xz}\sin\theta + \tau_{yz}\cos\theta) \quad \text{A6}$$

Appendix B: Stress transformation

Stress transformation of principal stresses (σ_h, σ_H, σ_v) with respect to inclination (γ), azimuth (φ) as follows [2]:

$$\sigma_x = (\sigma_h \cos^2\varphi + \sigma_H \sin^2\varphi)\cos^2\gamma + \sigma_v \sin^2\gamma \quad \text{B1}$$

$$\sigma_y = \sigma_h \sin^2\varphi + \sigma_H \cos^2\varphi \quad \text{B2}$$

$$\sigma_z = (\sigma_h \cos^2\varphi + \sigma_H \sin^2\varphi)\sin^2\gamma + \sigma_v \cos^2\gamma \quad \text{B3}$$

$$\tau_{xy} = \frac{1}{2}(\sigma_H - \sigma_h)\sin 2\varphi\cos\gamma \quad \text{B4}$$

$$\tau_{yz} = \frac{1}{2}(\sigma_H - \sigma_h)\sin 2\varphi\sin\gamma \quad \text{B5}$$

$$\tau_{xz} = \frac{1}{2}(\sigma_h \cos^2\varphi + \sigma_H \sin^2\varphi - \sigma_v)\sin 2\gamma \quad \text{B6}$$