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Analytical critical drawdown (CDD) failure model for real time sanding potential prediction based on Hoek and Brown failure criterion

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The risks of failure in sand reservoirs and consequent sand production is now a stark reality in the upstream oil and gas industry. As a result, failure analysis of reservoir rocks for sanding potential prediction purposes has become a routine activity more than ever before. Owing to the huge economic, operational and safety implications of risks of sand failure, the efficient management of these risks for field operation optimization requires a reliable failure model, which can capture the failure processes adequately in real time. Mohr coulomb failure criterion has been more widely applied for rock mechanics problems relating to sand failure analysis and production in the oil industry and elsewhere, and has been used as the basis or platform for more than 80% of the failure models being used in the industry today for rock failure analysis and sanding potential prediction. The major reasons for this could be attributed to: (a) simplicity in understanding and use and (b) description by a simple mathematical expression. The mathematical expression of Mohr Coulomb criterion defines shear stress as a linear function of the normal stress, which is depictive of a linear failure envelope. In addition Mohr Coulomb is only applicable to intact rocks and cannot be applied to already failed rock. Failure envelope in petroleum formation rock has however been proved to be non-linear and as such Mohr Coulomb failure criterion and the models based on it cannot be trusted to capture the failure processes adequately and reliably. In this study, Hoek and Brown failure criterion has been used as a platform to develop a new time-coupled analytical failure model for the analysis of sanding potential prediction in real time. The basis for using the Hoek and Brown failure criterion lies in its ability to capture rock failure as a non-linear process and applicability to both intact and failed rocks. This model has been tested and validated on some field data; in addition, it has been compared with another Mohr Coulomb-based drawdown failure model. The results obtained from the testing and validation scheme are very encouraging and show that Hoek and Brown criterion can indeed help overcome the inherent problems in Mohr Coulomb criterion.

Key words: Rock failure, sand prediction, failure criteria, critical drawdown, failure envelope, uniaxial compressive strength (UCS).

INTRODUCTION

Analysis of risk of failure in reservoir rock and potential for sand production is now a routine activity in the petroleum industry. Sanding potential prediction in real time is crucial and important to be able to make timely reservoir management decisions on the sand control methods or techniques to be deployed in any field. Conventional sand prediction techniques used in the industry today are based on field observation and experience, laboratory sand production experiments and theoretical or numerical modelling (Veeken et al., 1991). Only recently, neural network based technique evolved through the work of Kanj and Abousleima (1999).

Techniques based on field observation and experience usually attempt to establish a correlation using multi-variable linear regression between the data collected

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from a sand producing well and operational and field parameters relating to formation, completion and production e.g. strength, flow rate, drawdown etc. These correlations are usually established with a small selection from the vast assemblage of parameters that could possibly affect sand production. For example Stein and Hilchie (1972) and Stein et al. (1974) correlated sand production from the reservoir with production rate, neglecting the effects of other parameters that affect sand production. Operational parameters (for example bean-up pattern, flow rate and drawdown) affecting sand production are known to be many and to vary from field to field. Using just a small selection of these parameters and extrapolating the results from one field to another may give inaccurate sand production prediction.

Techniques based on laboratory sand production experiments involve observation and simulation of sand production in controlled laboratory environments. These experiments have suggested that sand production in unconsolidated sandstone is caused by the flow rate and capillary forces (Hall and Harrisberger, 1970) while in friable-consolidated sandstone, by boundary stress (Vriezen et al., 1975). Laboratory sand production experiments are usually performed on cores. The great setback of this technique is the fact that most wells are not cored, meaning that cores are not always available. Even when they are available, they may be affected adversely during retrieval, transportation and processing by a number of factors such as core damage, stress relief etc. All these add to the degree of uncertainty surrounding the results of laboratory sand production. Extrapolating these results to field conditions may therefore, constitute a source of error.

Techniques based on theoretical modelling suggest compressive failure, tensile failure and erosion as mechanisms responsible for sand production (Addis et al., 1998). Theoretical modelling also suggests that compressive failure can be triggered by both far-field stresses (depletion) and drawdown pressure; and tensile failure, exclusively by drawdown. Erosion is believed to occur when the drag forces exerted on a particle at the sand face exceed its apparent cohesion. However, theoretical modelling requires a mathematical approach to failure mechanisms (Veeken et al., 1991) and relies heavily on log-derived geomechanical parameters. However, the uncertainty in the formation strength obtained from log-derived parameter affects the reliability of theoretical modelling. Estimating formation strength from the mechanical properties log, may be inapplicable in some fields due to non-consolidation and high clay content (Cole and Ross, 1998). Often times these models are not validated with field sand production data, their results, in these circumstances, can best be described as qualitative.

Neural network based sand prediction was first reported by Kanj and Abousleiman (Kanj and Abousleiman, 1999). Parameters that were thought to affect production of sand in a gas well, were presented to a feed forward back propagation network (BPN) and a generalized regression neural network (GRNN) to predict important sanding indication parameters (SIP) for the gas wells of Northern Adriatic Basin. It was concluded that neural network proved capable of predicting sanding potentials with an unprecedented level of accuracy. However, the presentation of many input parameters to the network is capable of increasing the network complexity due to increased network size (Oluyemi et al., 2006). This may have a negative performance impact on the ability of the network to predict sanding potential accurately. In addition, one of the input data to the network - formation cohesive strength - can only be obtained using Mohr circles. Generation of Mohr circles is heavily dependent on core acquisition; this does not allow for real time sanding potential prediction.

PREDICTIVE SAND PREDICTION MODELS BASED ON MOHR COULOMB FAILURE CRITERIA MODEL

In recent times, predictive models and/or techniques based on the numerous failure criteria in use in the oil and gas industry have been more extensively used for sand prediction; most of these predictive models and techniques are based on Mohr Coulomb failure criterion. Essential features of some of the recently formulated and the most widely used of such models are discussed in the following paragraphs to underline their development framework and limitations.

McPhee and Enzendorfe (2004) and McPhee et al. (2000) developed a plastic (failed) extension model (PZE) based on Mohr Coulomb failure criterion. This is based on a yield zone approach that accounts for shear failure triggering sand failure, the existence of a plastic (failed) zone around perforations, and the effective stress state in near wellbore area. The calibration parameter used to define the critical conditions for sand production is the ratio of the plastic zone radius to the wellbore/perforation radius (r_p/r_w). The model is represented thus (equation 1):

$$\left[\frac{r_p}{r_w}\right]^{q-1} = \frac{q-1}{q+1}\frac{1}{C_o}\left\{2\sigma_h^{'}(t) - (2-\gamma)\left[P_i(t) - p(\infty,t)\right] + \frac{2C_o}{q-1}\right\} \tag{1}$$

Where:

r_p = radius of plastic zone, ft

r_w = radius of wellbore or perforation, ft

$$q = \tan^2\left(\frac{\Pi}{4} + \frac{\theta}{2}\right)\text{, in radian} \tag{2}$$

$\sigma_h^{'}$ = effective minimum horizontal stress (at time t), psi

$$\gamma = \frac{1-2\nu}{1-\nu} \qquad (3)$$

ν = Poisson ratio

θ = angle of internal friction (degree)

Pi (t) = Constant pore pressure around well (at time t), psi

p(∞, t) = far field (reservoir) pore pressure (at time t), psi

Co = uniaxial compressive strength, psi

Input parameters for the model include UCS (Co), frictional angle θ, Poisson ratio (ν), in-situ stress state – horizontal stresses, (σ_h' (t)), and well drawdown and planned depletion level – Pi (t) and p(∞, t).

Shear failure model used by BP in-house for sanding potential prediction is a stress-based model of shear failure around a perforation or an open hole wellbore (Wilson et al., 2002; Vaziri et al., 2002; Palmer et al., 2003) the mathematical representation is given in equation 4:

$$CBHFP \le \frac{3\sigma_1 - \sigma_3 - \sigma_y}{2-A} - P_r\frac{A}{2-A} \qquad (4)$$

CBHFP = critical bottom hole flowing pressure

P_r = current average reservoir pressure

σ_1 & σ_3 = the total principal major and minor stresses

A = poro-elastic constant (it is a function of Poisson ratio and formation compressibility)

σ_y = 3.1*TWC

The factor 3.1 includes the scale transformation from TWC laboratory sample (OD:ID = 3) to field (OD:ID = infinity).

Coates and Denoo (1981) model, based on Mohr coulomb theory, is also a shear failure model specifically developed for borehole stability analysis during drilling and sand prediction during production. The three principal stresses, x, y and z acting on a block of material deep down the earth bowel, are first written in terms of overburden stress, pore pressure and Poisson ratio as given in equations 5 - 7:

$$\sigma_x = \frac{\nu}{1-\nu}\sigma_{ob} + \alpha P_p\left(1 - \frac{\nu}{1-\nu}\right) \qquad (5)$$

$$\sigma_y = \frac{\nu}{1-\nu}\sigma_{ob} + \alpha P_p\left(1 - \frac{\nu}{1-\nu}\right) \qquad (6)$$

$$\sigma_z = \sigma_{ob} \qquad (7)$$

ν is Poisson ratio; σ_{ob} is overburden pressure; α is Biot poroelastic constant; and Pp is pore pressure.

The three stresses are then written as radial coordinates for ease of analysis during drilling; and then transformed in a manner similar to the popular Kirsch's stress transformation to radial systems of overburden, tangential and radial stresses (equations 8 - 10).

$$\sigma_z = \sigma_{ob} + 2\nu(\sigma_1 - \sigma_2) \qquad (8)$$

$$\sigma_\theta = 3\sigma_1 - \sigma_2 - P_{mud} \qquad (9)$$

$$\sigma_r = P_{mud} \qquad (10)$$

Analysis of the interplay between the radial and tangential stresses is then utilised for failure potential analysis in rocks and by extension sanding potential prediction.

Wang and Lu (2001) developed a model based on Equivalent Critical plastic strain. The model was implemented and developed using finite element numerical method by fully coupling a comprehensive geomechanic model to a multiphase reservoir model. The equivalent critical plastic strain level is considered as signifying the onset or initiation of hole collapse and sand production. The onset of plastic yielding, sand production and wellbore collapse, are defined based on a combined criterion in which stress concentration and strain are calculated and compared to critical strength and strain. Onset of wellbore instability or sand production is defined when the following criterion for effective or equivalent plastic strain is satisfied:

$$\varepsilon_e^p = a_o + a_1 J_1 = \sqrt{\frac{2}{3}\left[\left(\varepsilon_{11}^p\right)^2 + \left(\varepsilon_{22}^p\right)^2 + \left(\varepsilon_{33}^p\right)^2\right]} \qquad (11)$$

a_o = 0.02 and a_1 = 0.008 have been suggested for sand production, provided the compression is taken to be positive (Wang and Lu, 2001).

$J_1 = \sigma_{11} + \sigma_{22} + \sigma_{33}$ (J_1 is the first stress invariant) (12)

Linear poro-elastic and brittle plasticity model developed by Wu and Tan (2002) is an improvement on the earlier one by Wang et al. (1991). It is based on linear poro-elasticity and brittle plasticity with a critical equivalent plastic strain on cavity surface as the sanding criterion. Inclusion of the effect of residual strength in the plastic zone surrounding the cavity is the major improvement in this model. The inclusion is based on the assumption that rock is linearly poro-elastic prior to the peak strength and become brittle plastic after the peak strength is exceeded, and with the stress exceeding the peak strength, the strength of the rock reduces to its residual strength.

For this model, onset of sanding initiation is defined by the equivalent critical strain equation given in equation 13:

$$\varepsilon_e^p = \sqrt{\frac{2}{3}\left(N_r^4 + 1\right)\varepsilon_{\theta i}^p} \qquad (13)$$

Where N_r^4 is residual strength parameter related to the angle of internal friction and $\varepsilon_{\theta i}^p$ is the tangential plastic strain. The equations for calculating these parameters are given by Wu and Tan (2002).

One feature common to all the models discussed above is the Mohr Coulomb failure criterion platform for their formulation. However, as pointed out earlier, Mohr Coulomb failure criterion has two major shortcomings, which are: (a) Assumption of linearity of failure envelope and (b) Inapplicability in failed rock environment. The linear approximation of failure behaviour of rocks by Mohr-Coulomb is considered an oversimplification of the failure process whilst its inability to capture discontinuities in failed rocks constitutes a serious limitation of its capability to accurately capture failure process and mechanism as obtained in the field. The implication of this is that all the models discussed above cannot be applied for formation rocks with discontinuities. Besides, some of them are formulated using complex numerical solutions which may make their application technically demanding and unrealistic.

Hoek-Brown criterion was developed as a gap-bridging model to capture the non-linearity of failure envelope in rock and the influence of discontinuities in already failed rock (Hoek and Brown, 1980; Hoek and Brown, 1988). The criterion was developed based on field, laboratory and theoretical considerations as well as experience, which makes it applicable to both intact and failed rocks. The criterion has therefore been used as a platform for the development of a sanding potential prediction model in this work; the developed model is simple and easy to use.

CRITICAL DRAWDOWN FAILURE MODEL FORMULATION

Hoek-Brown failure criterion is given mathematically as (Hoek and Brown, 1980; Hoek and Brown, 19880):

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_{ucs}\sigma_3 + s\sigma_{ucs}^2} \qquad (14)$$

Where σ_1 and σ_3 are effective principal stresses; m and s are constants; and σ_{ucs} is uniaxial compressive strength.

At the borehole wall the effective principal stresses σ_1 and σ_3 in equation (14) can be represented respectively by the effective tangential, σ_θ and radial, σ_r stresses. Equations for estimating both the tangential (for both maximum and minimum horizontal stresses) and radial stresses are given as (Abass et al., 2003):

$$\sigma_{\theta_a \equiv 90} = 3\sigma_H - \sigma_h - p_w \qquad (15)$$

(where azimuth $\theta_a = 90$)

$$\sigma_{\theta_a \equiv 0} = 3\sigma_h - \sigma_H - p_w \qquad (16)$$

where azimuth $\theta_a = 0$

$$\sigma_r = p_w \qquad (17)$$

The Hoek-Brown failure criterion can therefore now be expressed in terms of the radial and tangential stresses, as given in equation (18):

$$\sigma_\theta = \sigma_r + \sqrt{m\sigma_{ucs}\sigma_r + s\sigma_{ucs}^2} \qquad (18)$$

Substituting equations (15) and (17) (for estimating tangential and radial stresses respectively) in equation (18) and rearranging, we have:

$$3\sigma_H - \sigma_h + 2\left(\alpha P_r - P_w\right) = \sqrt{m\sigma_{ucs}\left(P_w - \alpha P_r\right) + s\sigma_{ucs}^2} \qquad (19)$$

The parameter, α, introduced in equation (19), is a scaling factor called Biot's or poroelastic constant, which measures the effectiveness of the pore pressure response to the total applied stress (Brandt, 1955). Its value, which depends on the pore geometry and the physical properties of the constituents of the solid system, varies between 0 and 1 depending on the effectiveness of its response to the total applied stress. In this work, pore pressure response to the total applied stress is assumed to be 100% effective. However, this may not be true for formations at advanced stages of depletion; there may therefore be need for either model or data adjustment or recalibration to account for this in such formations.

Therefore let α = 1; and $y = CDD_i = \left(P_r - P_w\right)$. Replacing pressure drawdown term in equation (19) with y and taking the square of both sides, we have,

$$\left((3\sigma_H-\sigma_h)+(2y)\right)^2=m\sigma_{ucs}(P_w-P_r)+s\sigma_{ucs}^2 \qquad (20)$$

Expanding the left hand side of equation (20) and rearranging, we have:

$$4y^2+4(3\sigma_H-\sigma_h)y+(3\sigma_H-\sigma_h)^2=m\sigma_{ucs}(P_w-P_r)+s\sigma_{uc}^2 \qquad (21)$$

Let A = $(3\sigma_H-\sigma_h)$; Substituting for A in equation (21) and rearranging, we have:

$$4y^2+4Ay+A^2+m\sigma_{ucs}(P_r-P_w)-s\sigma_{ucs}^2=0 \qquad (22)$$

Recall that (P_r-P_w) = y; replacing the new pressure drawdown term in equation (22) with y and rearranging, we have:

$$4y^2+(4A+m\sigma_{ucs})y+(A^2-s\sigma_{ucs}^2)=0 \qquad (23)$$

Equation (23) is a quadratic equation and can be solved using the solution of a quadratic equation. The equation can therefore be written in the form of a general quadratic equation given in equation (24):

$$ay^2+by+c=0 \qquad (24)$$

The solution of the quadratic equation of this form can be written as:

$$y=\frac{-b\pm\sqrt{b^2-4ac}}{2a} \qquad (25)$$

If equation (23) is matched with equation (24), then a = 4; b = $(4A+m\sigma_{ucs})$; and c = $(A^2-s\sigma_{ucs}^2)$

Substituting these parameters in equation (25) and recalling that y = (P_r-P_w) = CDD$_i$, we have

$$CDD_i=\frac{(4A+m\sigma_{UCS})\pm\sqrt{(4A+m\sigma_{UCS})^2-16(A^2-s\sigma_{UCS}^2)}}{8} \qquad (26)$$

The developed mechanistic model shown in equation (26) is coupled to time by using a term which describes reservoir formation depletion profile in a similar manner to the work of Hettema et al. (2006). The resulting time-coupled equation is given in equation (27).

$$CDD_c=\left[\frac{(4A+m\sigma_{UCS})\pm\sqrt{(4A+m\sigma_{UCS})^2-16(A^2-s\sigma_{UCS}^2)}}{8}\right]-\left[n\frac{(P_{ri}-P_{rc})}{1}\right] \qquad (27)$$

P$_{ri}$ is the initial reservoir pressure before the start of production; P$_{rc}$ is the current reservoir pressure as a result of depletion; and n is a dimensionless parameter, which represents the ratio of change in critical drawdown pressure with reservoir depletion. Hettema et al. (2006) suggests that n = 1 when drawdown and depletion are equally important for sand production, which is the case in this work. Equation 27 is a mechanistic model for predicting the current critical drawdown (CDD$_c$) of reservoir formation rock (wrt time) which, when exceeded either during drilling or production, would result in failure of the formation and by extension, sanding. Input parameters into the model include field minimum and maximum horizontal stresses, uniaxial compressive strength (UCS), and Hoek and Brown constants which are readily available.

HOEK AND BROWN ESTIMATES OF MODEL CONSTANT PARAMETERS

Hoek and Brown (1988) developed, based on a series of experimental work, estimates of m and s for a wide range of rocks under a wide range of conditions that can be encountered in petroleum formation rocks.

The estimated values of these parameters reflected the level of disturbance undergone by the rock formations. The estimates as given by Hoek and Brown (1988) are given in Table 1. These estimates can be used for the constant terms m and s in the CDD model developed in this work. Caution must however be exercised in their use especially in situations where it is difficult to assign formation rock to the correct failure state.

ANALYSIS, TESTING AND VALIDATION OF MODEL

Two sets of North Sea field data, obtained from Field A and B were used to analyse, test and compare the CDD model (Equations 26 and 27) with another onset of sand prediction model developed by Abass et al. (2003). Abass et al. (2003) model was used for the comparison because of its similarity to the model developed in this work in terms of input parameters and availability of the input data. The results are shown in Figures 1 - 6 and Table 2.

Figure 1 shows the results obtained when data from Field A was utilised for comparison of the performance of the current model with Abass et al. (2003) model in terms of accurate and reliable predictions of Critical Drawdown for Field A. The results, as shown in the Figure, indicate

Table 1. Hoek and Brown (11) estimates of m and s.

Rocks	**Carbonates rocks E.g limestone**	**Lithified argillaceous rocks e.g. shale**	**Arenaceous rock e.g. sandstone**	**Fine grained igneous rocks e.g. rhyolite**	**Coarse grained igneous rocks e.g. granite**
Intact rocks	M=7 S=1	M=10 S=1	M=15 S=1	M=17 S=1	M=25 S=1
Undisturbed rocks	M=4.10 S=0.189	M=5.85 S=0.189	M=8.78 S=0.189	M=9.95 S=0.189	M=14.63 S=0.189
Moderatly weathered rocks	M=9.2-2.0 S=0.00198-0.0205	M=1.35-2.86 S=0.00198-0.0205	M=2.03-4.298 S=0.00198-0.0205	M=2.301-4.871 S=0.00198-0.0205	M=3.383-7.163 S=0.00198-0.0205
Heavily weathered rocks	M=0.219 S=0.00002	M=0.313 S=0.00002	M=0.469 S=0.00002	M=0.532 S=0.00002	M=0.782 S=0.00002

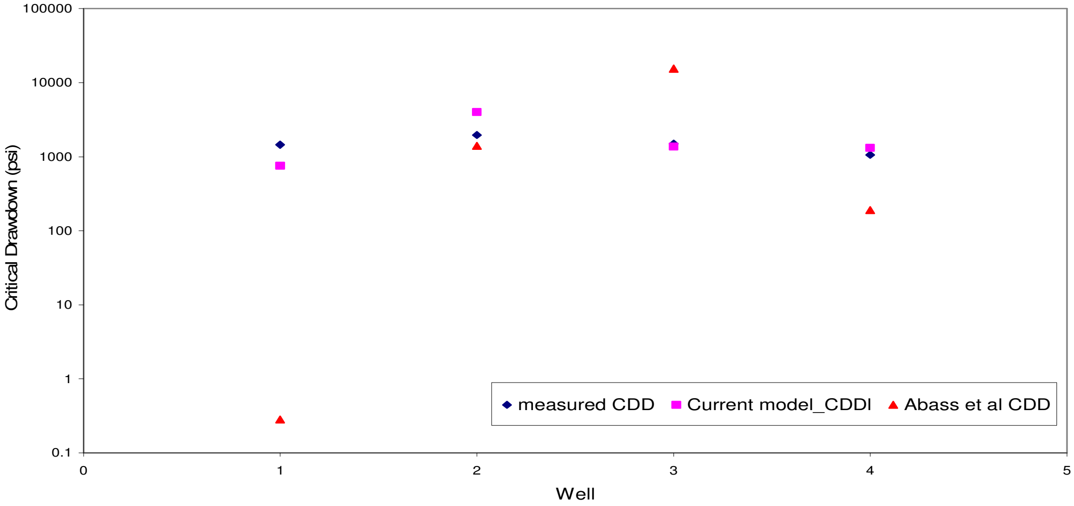

Figure 1. Comparison of CDD model with Abass et al. CDD model using a North sea field data (field A).

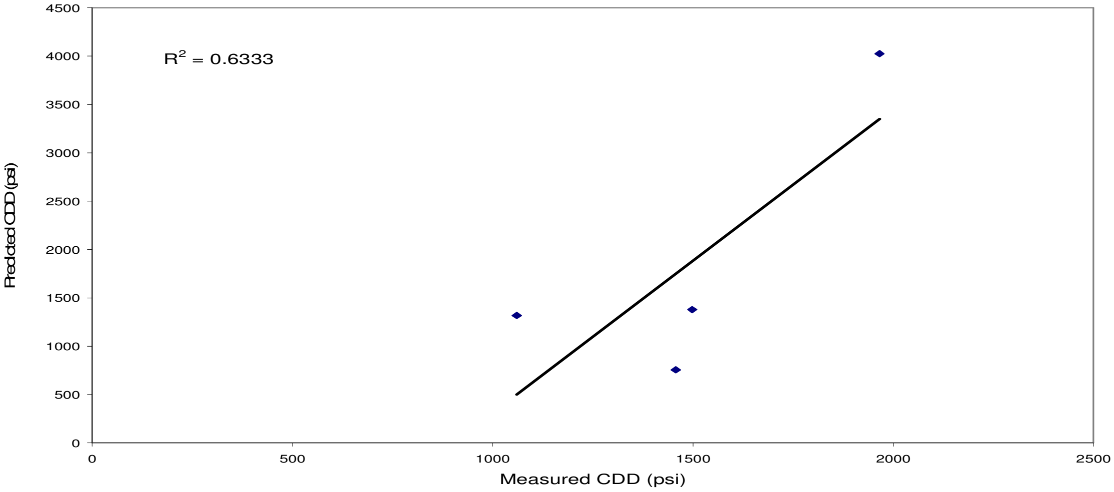

Figure 2. Correlation coefficients of predicted versus measured CDD for the current model (field A).

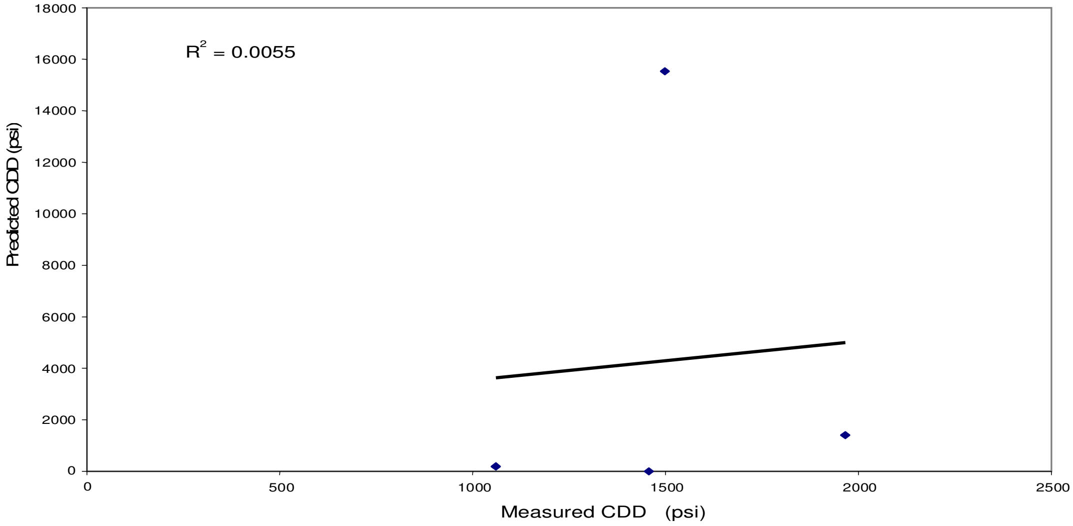

Figure 3. Correlation coefficients of predicted versus measured CDD for Abass et al model (Field A).

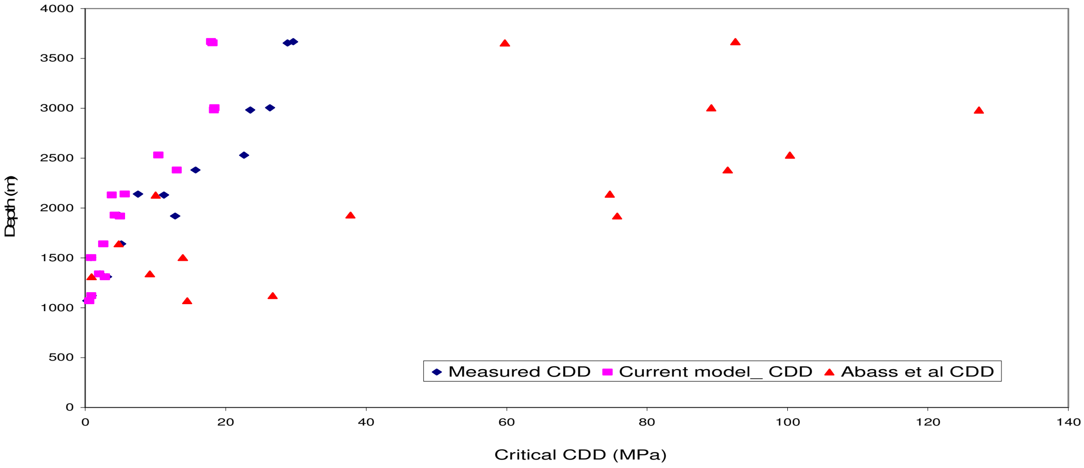

Figure 4. Comparison of CDD models with Abass et al. CDD models using a North Sea field data (Field B).

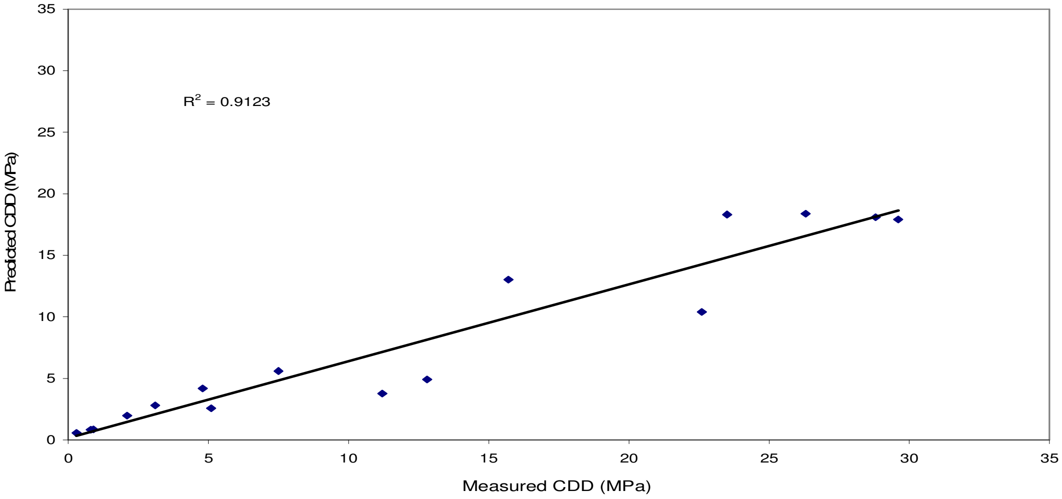

Figure 5. Correlation coefficients of predicted versus measured CDD for the current model (Field B).

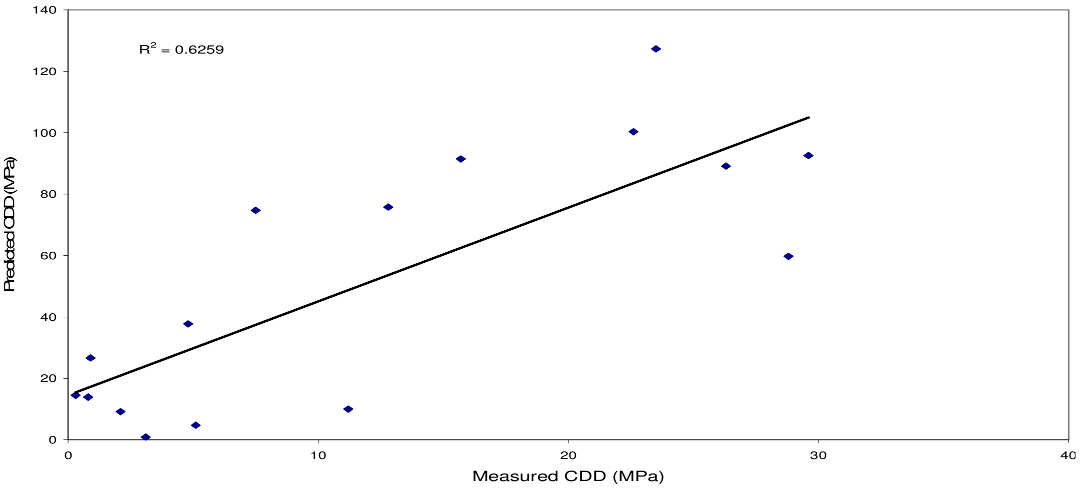

Figure 6. Correlation coefficients of predicted versus measured CDD for Abass et al. model (Field B).

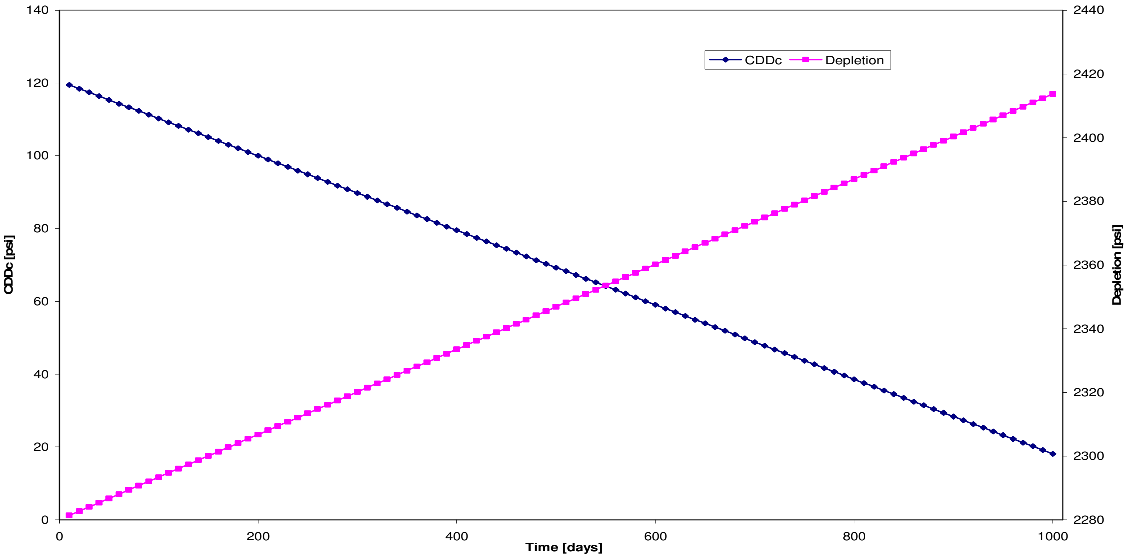

Figure 7. CDD predictions in real time for a North Sea well at 17000ft.

Table 2. Correlation coefficients.

Model	Field A	Field B
Current model	0.6533	0.9123
Abass et al. model	0.0053	0.6259

that the current model's predictions agree better with the measured CDD than Abass et al. (2003) model's predictions. The correlation coefficients between the predicted CDD by the two models and measured data are shown in Figures 2 and 3. The current model's predictions have a correlation coefficient of 0.6333; whilst for Abass et al. (2003) model's predictions, the correlation coefficient is 0.0055, which is undoubtedly poor.

Figure 4 shows the results obtained from the use of Field B data; the results also indicate that the current model's predictions are closer to the measured CDD much more than Abass et al. (2003) model' predictions. Determination of the correlation coefficients for the models' predictions for Field B data shown in Figure 5 and 6 shows that the current model's predictions have a correlation coefficient of 0.9123 whilst Abass et al. (2003) model predictions have a correlation coefficient of 0.6259, again showing that the current model has a better predictive capacity and exhibits better reliability. Shown in Figures 7 and 8 are the examples of CDD

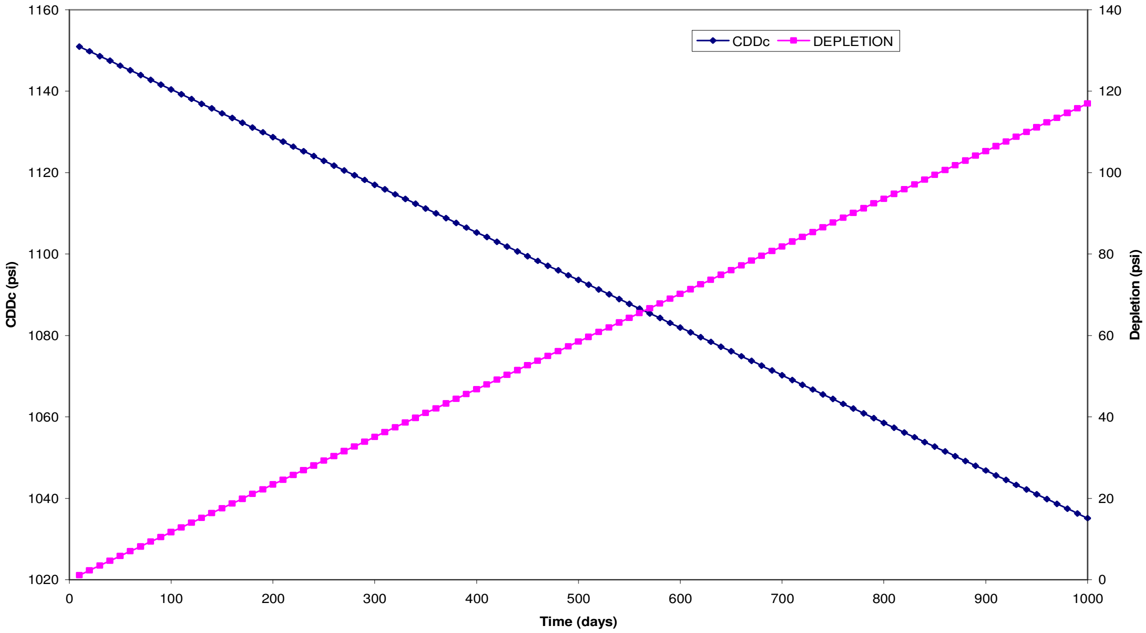

Figure 8. CDD predictions in real time for a North Sea well at 6412ft.

profiles obtained from real time prediction of critical drawdown (CDD) by the time coupled variant of the CDD model (equation 27) for a North Sea well at 6412 ft and 17000 ft.

In summary, the results show that the CDD model developed in this work has a better predictive capability than the corresponding model developed by Abass et al. (2003).

Conclusion

Many of the most widely used predictive models for predicting sanding potential and sanding initiation in the oil and gas industry are developed using Mohr Coulomb failure criterion as a platform for their development. Mohr Coulomb criterion is however, not able to capture the failure process adequately and accurately due to the assumption of non linearity of failure envelope. To address this problem, a new model for predicting sanding potential has been developed using Hoek and Brown failure criterion as a platform. The model has been tested, analysed and validated against a Mohr Coulomb based sand initiation model and found to perform better.

Nomenclature

r_p = Radius of plastic zone

r_w = Radius of well/perforation

θ = Angle of internal friction

υ = Poisson ratio

$\sigma_h^{'}$, $\sigma_H^{'}$ = Effective minimum and maximum horizontal stresses.

$p(t)$ = Constant pore pressure around well at time t

$p(\infty, t)$ = Far field reservoir pressure at time t

σ_{ucs}, C_o = Uniaxial compressive strength

CBHFP = Critical bottom hole flowing pressure

p_r = Current average reservoir pressure

σ_1, σ_2, σ_3 = Total principal stresses

A = Poroelastic constant

TWC = Thick Walled Cylinder strength

σ_{ob} = Overburden stress

σ_x, σ_y, σ_z = Principal stresses acting in x, y and z directions

α = Biot poroelastic constant

p_{mud} = Mud column pressure

CDD = Critical drawdown pressure

CDD_i = Initial Critical Drawdown

CDD_c = Current Critical Drawdown

σ_r = Radial stress

σ_θ = Tangential stress

ε_e^p = Effective or equivalent plastic strain

ε_{11}^p, ε_{22}^p, ε_{33}^p = Plastic strain in reference directions

J_1 = First stress invariant

p_w = Wellbore pressure

P_{ri} = Initial reservoir pressure

P_{rc} = Current reservoir pressure

N = Ratio of change in critical drawdown pressure with reservoir depletion.

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