Rock Property Modelling Workflows

Establishing the mechanical and flow properties of formations involves many techniques that have successfully been applied in the oil and gas industry. These properties are required for drilling a well safely, choosing an optimal lower completion method, for hydraulic fracturing and stimulation design or for the determination of reservoir and well compaction. When wells are completed in sand production prone environments, a sand prediction tool can assist in the decision point between cased and conventional perforating techniques, orientated perforating or the use sand exclusion devices. For a gravel pack or ESS, the tool should provide a means to determine when plugging will be initiated. The massive failure envelope can provide a means to quantify when an expandable sand screen may collapse.

This white paper focuses on the sand prediction methodologies utilised by Sapella in the development of the Ta2ooine numeric model. Modern operations require that Reservoir Surveillance Engineers and Production Technologists utilise tools to determine whether a formation can be perforated either conventionally or using orientated guns, or whether a retrofit sand control device will be required. The main advantage of this type of an all-encompassing software tool, is that results are immediately available and can be matched during all phases of field life, but in particular during the initial depletion stages of the reservoir. Matching during the initial production phase is key to allow alteration and optimization of lower completions early.

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Sand Management Option: Control or Prevention?

Dependent upon lithology, flow rate and type, in-situ stresses, formation strength, perforation orientation and type, sand may be produced along with oil, gas and water. Changes in flow rate related to pressure drawdown, increasing effective stress due to depletion and increasing water production with time are the main factors that result in sand production.

Sand control utilizes mechanical methods to exclude sand from produced fluids. Sand prevention incorporates techniques to minimize or eliminate the amount of sand produced and to reduce the impact of produced sand without mechanical exclusion methods. Choosing between these options is a function of perforation and formation stability and whether perforation failure can be predicted. The essence of sand management is quantification of sand production risk, which helps operators decide if, how and when sand control or sand prevention should be implemented.

Several methods help predict perforation tunnel stability over the life of a well. Theoretical borehole stability models adapted to perforations are useful in predicting perforation stability as stress conditions change due to pressure drawdown and depletion. Experimental methods involve testing reservoir cores or outcrop rocks with similar properties. Sand-prediction criteria based on production history, by far the most widely used technique, rely on experience from other wells and correlation of rock strength to calibrate theoretical models and help choose between sand control and/or sand prevention.

Sand Prediction Strategies

Hence, there are several strategies that have been developed for predicting the potential for solids production:

- Field experience and empirical observation (from existing wells)
- Laboratory experiments
- Computation of wellbore stresses and comparison to rock failure criteria
- Yield zone growth
- Numerical modelling

Sanding evaluation based on field experience, where no analytic or numerical solutions are used, is the most simplistic appraisal and is a valid method for sanding prediction. Unfortunately, the technique relies on having sufficient experience and confidence to extrapolate previous results to new wells. Problems can arise from this approach if unanticipated geologic conditions are encountered in new wells, reservoir and fluid properties vary from those in the base case well(s), or if the observed performance of vertical wells is extrapolated to either open hole or deviated wellbores.

Laboratory experiments generally involve the testing of core samples, arching experiments, or sanding initiation tests. The most common tests involve the compressive destruction of Thick Wall Cylinder (TWC) or solid core plug samples. This destructive testing provides data that are then used for the calibration of numeric models.

Note however, that the results obtained from laboratory tests are difficult to accurately scale up to the actual wellbore environment, and as such do not provide a direct tool for the prediction of rock failure under production conditions. The results from any tests conducted must be treated as rock strength index data, and cannot be used in isolation, but must be combined with other empirical data and analytic calculations.

Using an analytic or numeric model to compare the calculated in-situ stresses with a predetermined failure criterion is the standard technique currently used in the industry.

The two main requirements are an appropriate failure criterion and an applicable analytic or numeric model. Most models assume that the formation is either elastic or poroelastic, and use strengths measured from logs, laboratory tests (core), scratch tests, or offsetting data.

Main Advantages of Numerical Modelling

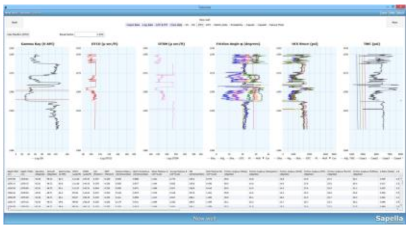
The main advantage of numerical techniques is that they are more appropriate for modelling the extent of instability around a borehole and can allow for the stress relaxation in any resulting plastic failure regions. This is particularly relevant in the case of deviated wellbores, where the onset of shear failure calculated by simple elastic models or laboratory testing does not necessarily signify the actual onset of sanding. The support of the casing and cement, and the geometry of the perforations in relation to the principal stresses and the bore hole act to hold the failed formation in place and must be accounted for in any model.

Numerical Modelling Workflow

The detailed workflow developed by Sapella is presented in Figure 1. The workflow typically consists of the following steps:

- Calculate in-situ stresses at initial reservoir conditions. Stresses consist of vertical stress, minimum and maximum horizontal stress.

- Calculate the mechanical properties for the formation of interest.



- Calibrate the mechanical properties. If core data is available, apply the core data and determine lab scaling and boost factors for the zone of interest.
- Run the transform, to calculate the polar in-situ stresses on the formation.
- Apply a failure criterion model.
- Generate load and drawdown factor plots.

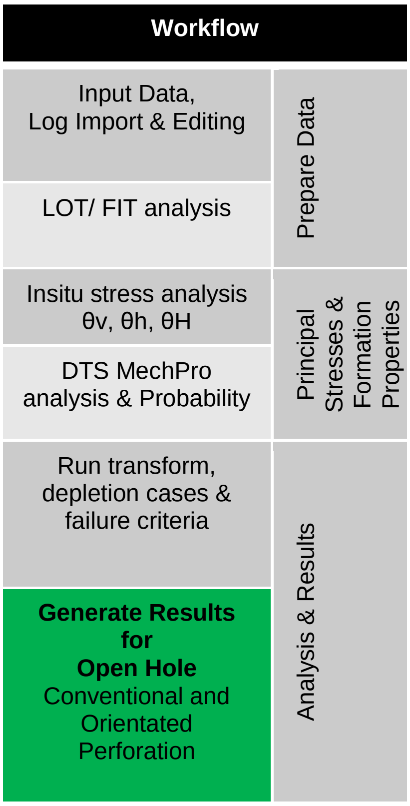


Figure 1: Technical Workflow

Calculate In-situ Stresses

The process of calculating the in-situ stresses uses accepted industry techniques developed by the drilling industry. The procedure is well documented and applied in most new well designs.

Step 1: Calculate the three stresses in the cartesian system at initial reservoir conditions.

Step 1a: Vertical stress is derived from the Bulk Density Log (RHOB). To increase the accuracy of the vertical stress profile, a well with a large coverage of RHOB signals is selected. The density is the main input for the vertical stress determination.

Step 1b: Calculate the minimum horizontal stress from Leak-off (LOT) or Formation Integrity (FIT) tests. These results are normally included in the Drilling End of Well Reports (EOWR).

Step 1c: Unless Differential Strain Curve Analysis (DSCA) has been performed, a default multiplier is used to calculate the maximum horizontal stress.

Step 2: A transform converts the in-situ stresses from Cartesian to a Polar System corresponding to the inclination and azimuth of the actual wellbore.

Calculate Mechanical Properties

A standalone MechPro (Mechanical Properties) module fully incorporated into Ta2ooine is utilised to compute the mechanical properties of the formation using various correlations. Outputs are used in sanding initiation determinations, fracturing design, as well as compaction and subsidence studies. The default methodology was developed by Bruce, but for flexibility numerous additional correlations are also included.

MechPro generates continuous (along hole) properties such as:

- Biot's constant and Poisson's Ratio
- Friction Angle
- Young's and Bulk modulus
- Effective uniaxial compressive strength (UCS)
- Thick walled cylinder strength (TWC)

The final output utilised by Ta2ooine is the TWC. There are two general algorithms in use, developed by the research departments of BP (Bruce), and Shell (Veeken and Palmer).

Bruce derived the basic formula for UCS (**Unconfined** compressive strength):

$UCS_{Bruce} = (26000 * E * K_b * a_{Ratio}) * (0.008 * V_{sh} + 0.0045 * (1 - V_{sh}))$

Dependencies exist on:
V_{sh}, Shale content = Gamma Ray
ν, Poisson's ratio = f(DTSM, DTCO)
K_b, Bulk modulus = f(DTSM, DTCO)
E, Young's Modulus = f(ν, K_b)
a_{Ratio} = f(Friction angle)

Veeken and Palmer developed alternative but similar methods to convert calculated rock properties to in-situ TWC in unconsolidated sandstones:

- TWC_{Veeken} = f(RHOB, DTCO)
- TWC_{Palmer} = f(UCS_{Bruce})

The TWC is the **confined** thick wall cylinder strength. Sapella has found that under certain circumstances the average using the TWC values from each method provides the most accurate estimate.

If sand strength data is available from laboratory testing, then the final effective formation TWC can be determined from (Willson et al.)

$TWC_{eff} = CF \times BF \times TWC_{ave}$

Matching to TWC Laboratory Results

Veeken and Davies determined experimentally that there is a linear relationship between the initial collapse of TWC samples, and the actual equivalent well bore stress, as shown in Figure 2. In Ta2ooine, this factor is referred to as the laboratory calibration factor (CF), and has the recommended default value of 0.86.

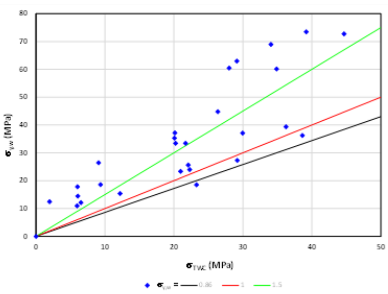


Figure 2 - Taken from SPE-22792 "Sand Production Prediction Review: Developing an Integrated Approach"

The CF factor should not be confused with the Laboratory Scaling Factor (LS) developed by Van Hoek and Milton-Taylor through a Joint Industry Project (FracTech Laboratories PEA135 - Sand Production Prediction).

Typical TWC samples have an OD to ID ratio of 3:1, while the ratio of an actual well or perforation to the reservoir is essentially infinity. Values derived both analytically and experimentally have demonstrated that the TWC strength multiplier increases with an increasing OD:ID ratio and tends to a constant of approximately 1.55. The derived correlation is presented in Figure 3.

It should be noted that as this correlation is somewhat controversial, it has been implemented as an option in Ta2ooine, with a default value of 1.0.

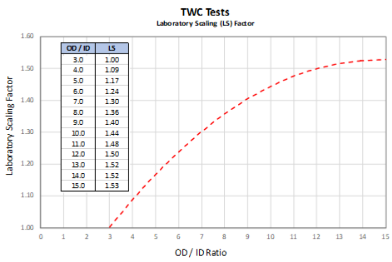


Figure 3 - From D. Milton-Taylor "Sand Management Network Presentation", Aberdeen, November, 2002

To convert the measured linear-elastic TWC strength to the equivalent elastoplastic behaviour in Ta2ooine, an additional "adjustment factor" is required. This factor is generally referred to in the industry as the "Boost Factor" (BF).

In Ta2ooine, the default value of the Boost Factor is 1.07, which corresponds to the initial inner wall failure of a TWC sample during testing. This value also closely approximates the theoretical Mohr-Coulomb (linear-elastic) initial sand failure point. A BF value of 2 is equivalent to the rupture of the outer wall of the TWC (massive failure), and the "industry norm" of 1.5 is the Root Mean Square (RMS) or "average value" between the two extremes of initial and massive failure.

A user of the software can easily adjust the boost factor to match core test data or data obtained from flow tests or production logging. Note that as production conditions change (reservoir depletion) the Boost Factor may need to be adjusted from the initial value.

Importance of Sonic Travel Time Values (Sonic Log Data)

In all geomechanical models, dipole sonic tool measurements, which provide both compressional (DTCO) and shear (DTSM) travel times, are used to calculate the dynamic elastic properties of the rock:

ν - Poisson's ratio = f(DTSM, DTCO)
K_b - Bulk modulus = f(DTSM, DTCO)
E - Young's Modulus = f(ν, K_b)
a_{Ratio} = f(Friction angle)

These elastic properties are then converted into rock strengths using empirical correlations and analytic calculations.

In many cases, a sonic log will not have been run. In these cases, synthetic log data will be required to generate the required mechanical properties. Ta2ooine, unique in the industry, has the capability of generating synthetic sonic data using multivariate data regressions rather than relying on simple empirical correlations.

Based on Sapella's experience, and discussions in the petroleum literature, the use of calibrated synthetic sonic data has proven to be the most accurate calculation procedure. Note that for completeness, Ta2ooine also contains the most used empirical correlations for generating synthetic sonic data.

Biot-Gassman Fluid Substitution

The response of compressive sonic logs is greatly affected by gas and to a lesser extent by oil. To compensate for this effect, a fluid substitution technique developed by Biot-Gassman has been implemented in Ta2ooine. The objective of implementing this model was to correct the compressive and to a lesser extent the shear sonic travel times for the presence of gas.

Figure 4 illustrates the effect and shows that even a low gas saturation has a large effect on the compressional travel times.

The effect on the shear sonic is opposite to that on the compressive and its magnitude is very marginal as fluids cannot be "sheared". That is, the effect on the shear travel time is it is only due to the changed density of the pore fluid, not due to the characteristics of that pore fluid.

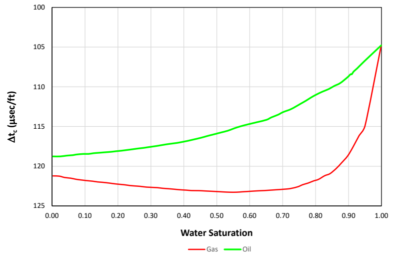


Figure 4 – Effect of Fluid Saturation on Compressional Sonic Velocity (DTCO)

Final Transform of Stresses and Application of Failure Models

To simplify the calculations, a coordinate transformation on the principal stresses (σ_V, σ_H, σ_h) from the Cartesian coordinate system (x, y, z) to a "wellbore based" rectangular coordinate system is performed, as illustrated in Figure 5.

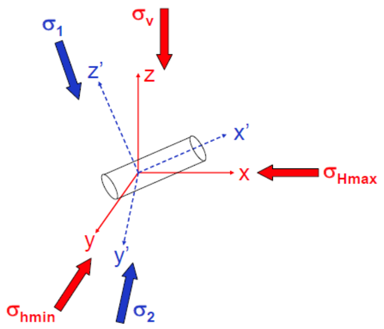


Figure 5 - Coordinate Transform from Cartesian (X, Y, Z) to Wellbore (X', Y', Z')

In the transformed system, the principle earth stresses (σ_V, σ_H, σ_h) are now expressed in terms of normal (σ_1, σ_2, σ_3) and shear stresses (τ_{12}, τ_{23},τ_{13}) as shown in Figure 6. For clarity, not all shear stresses are plotted.

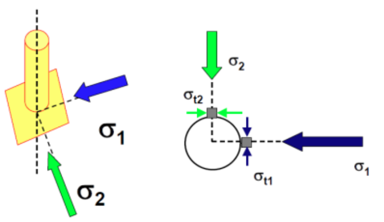


Figure 6 – Resulting Wellbore Stresses after Coordinate Transform

The Kirsch equations are then used to transform these far field stresses into the equivalent borehole stresses expressed in polar coordinates (σ_θ, σ_H, σ_z, $\tau_{\Theta\Theta}$, $\tau_{\Theta z}$, τ_{rz}). This makes it possible to determine the principle stresses acting at the cavity wall, as shown in Figure 7.

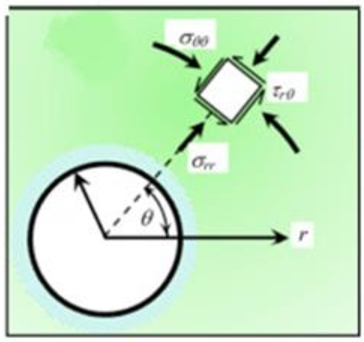


Figure 7 - Far Field Radial Stresses

Due to this formulation, Ta2ooine can model open hole, slotted liner, screened, and cased and perforated completions, at any azimuth or deviation. Azimuth in the model, as shown in Figure 8, is always measured with respect to the direction of the maximum horizontal stress (σ_H).

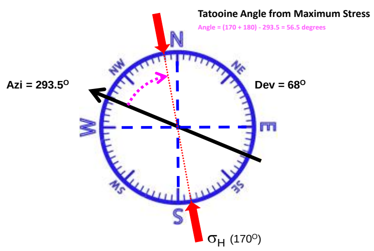


Figure 8 – Determination of the Maximum Stress Angle from the well azimuth in relation to the maximum horizontal stress

For cased and perforated completions, Ta2ooine calculates the failure condition for perforations oriented between 0° and 90° (at 10° intervals). To clarify, the modelled perforation orientation in Polar Coordinates is presented in Figure 9.

Due to wellbore symmetry, only one quarter (0° to 90°) of the perforations are modelled.

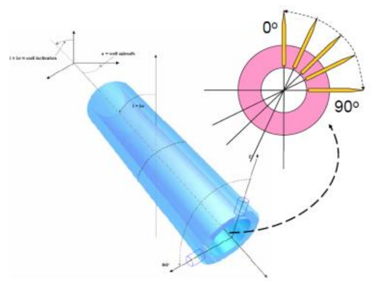


Figure 9 - Illustration of Perforation Orientation in Polar Coordinate System

Results

Open hole

Ta2ooine provides industry norm operating envelopes for values where open hole initial failure or subsequent massive failure will occur. Compaction and subsidence values can be calculated simultaneously.

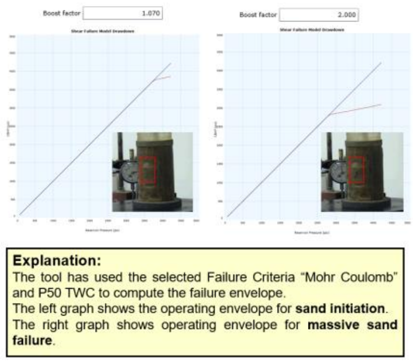


Figure 10 – Open hole sand failure initiation and massive failure operating envelopes

Cased-hole Conventional Perforations

In case the sand strength is calculated to be of moderate strength, the failure envelope can be calculated as above for a cased and conventionally perforated zone. Figure 11 illustrates the case where the critical drawdown is small for a sand of low strength.

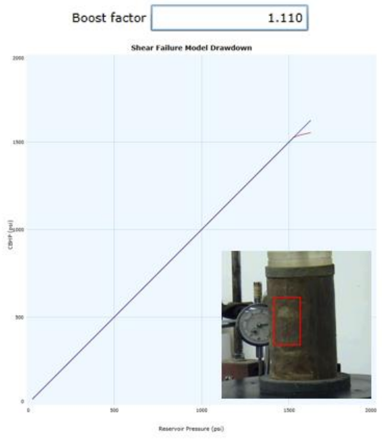


Figure 11-Cased-hole sand failure initiation operating envelope

Cased-hole Orientated Perforations

For the case when a formation has an intermediate strength, it may be possible to use oriented perforations rather than resorting to physical sand exclusion such as a screen in a cased-hole environment. The software provides a workflow to assist in this decision. For a cased and perforated completion, Ta2ooine calculates the failure condition for perforations oriented between 0° and 90° (at 10°) intervals to the top dead centre (TDC) of the well, and generates a Load Factor Plot as shown in Figure 12.

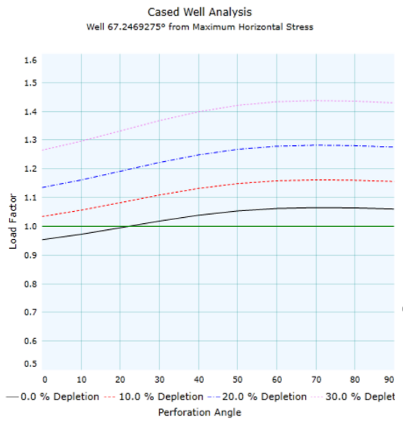


Figure 12 – Load Factor Plot for the determination of the effectiveness of oriented perforations. A Load Factor greater than 1.0 indicates failure

For clarity, the model's perforation inclination is illustrated in Figure 13. Again, due to wellbore symmetry, only one quarter (0° to 90°) of the perforations need to be modelled.

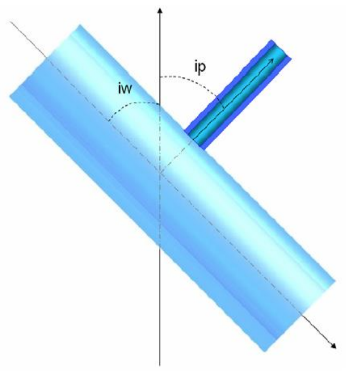


Figure 13-Perforation orientation

Sand Plugging in an ESS, slotted liners or gravel pack completions

The open hole modules in Ta2ooine can be utilised to establish when an ESS may fail. Expandable sand screens have little collapse strength, hence Ta2ooine provides a means to define the operating envelope for massive sand failure.

Drawdown Model

The second tool provided by Tatooine for sanding evaluation is a Shear Failure Drawdown model. The model calculates the maximum potential sand free drawdown for a specified perforation angle, and then plots the results. Plot axes are Bottom Hole Flowing Pressure (BHFP) and the Reservoir Pressure (P_{Res}) at any given time. The plot is used to examine various combinations of potential reservoir pressures and bottom hole flowing pressures. The resulting operational envelopes define–depletion conditions that are likely to result in sanding.

Figure 14 presents an example of such a plot where the results for a range of perforating angles are plotted, and the reservoir pressure versus bottom hole flowing pressure is included. Any point "above" the perforation line represents sand free production for that perforation angle.

The pressure points were obtained from simulation runs, and are yearly averages calculated by summing daily pressures and dividing by the number of production days. The labels on the simulated points are the year that the pressures will be reached.

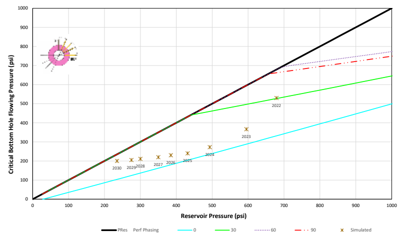


Figure 14 – Ta2ooine Drawdown Failure Model illustrating that selective perforating (0 – 30 degrees) could be an effective sand mitigation strategy for the simulated reservoir depletion scenario.

Studies

Ta2ooine provides the operator with a detailed high-tech solution to make lower completion decisions in depleting reservoirs. Studies have been completed by many operators for

- Lower completion installation decisions
- Subsidence and compaction studies
- Orientated perforating versus conventional perforating
- Open hole massive failure envelopes
- Fracture designs

The models available for geomechanical properties are relatively reliable, even more so if they are matched with historical field data.

Summary of Workflow

This paper has summarised the technical workflow. The organisational workflow is just as important. With use of the software, once base assumptions for the log .las file output have been discussed with the Petrophysicist, the Petroleum, Reservoir can build detailed geomechanical models for any perforation or completion program. An advantage is that the tool enables the operational engineer to provide decisions for any geomechanical problem, revisit the models as new data comes in during field life to match the Ta2ooine geomechanical models accordingly. This is not possible if geomechanical studies are conducted externally, as the models for software runs are not readily available.

Differentiators

Ta2ooine is a full 3D software application package that estimates the probability of mechanical failure in the near wellbore. Using empirical and analytic formulations scaled to laboratory Thick Wall Cylinder

(TWC) test data, Ta2ooine can predict sand failure in horizontal, deviated, and vertical wells for both open hole or cased and perforated cases.

Ta2ooine is a unique tool in that it was developed by production and completions engineers for use in daily operations. Most available borehole stability models have been developed by major service providers as an adjunct to their existing petrophysical and/or geophysical software. These proprietary models require a high level of specialized knowledge and training to run and are generally not available to, or usable by engineering staff.

The design of the software reflects the geomechanical studies workflow. The programme consists of screens that can be accessed through tabs and the order of the tabs describe the workflow, so the user is guided through the simple software design to obtain results easily.

In all geomechanical models, dipole sonic tool measurements, which provide both compressional (DTCO) and shear (DTSM) travel times, are used to establish the dynamic elastic properties of the rock. These elastic properties are then converted into rock strengths using empirical correlations and analytic calculations. The largest differentiator between Ta2ooine and other models, is it has the capability of generating synthetic sonic data using multivariate data regressions rather than relying on simple empirical correlations. Based on Sapella's experience, and discussions in the petroleum literature, the use of calibrated synthetic sonic data has proven to be significantly more accurate than the commonly applied empirical correlations.

The model can also directly calculate the change in horizontal stress that results from the increase (from injection) or decrease (depletion) of pore pressure. This calculated stress regime is less conservative than in traditional applications and provides Ta2ooine with the ability to generate operating envelopes over the entire field life, from initial pressure to full depletion.

Nomenclature

CF Laboratory calibration factor

BF Boost factor

EOWR End of Well Report

ESS Expandable sand screen

LS Laboratory scaling factor

TWC Thick walled cylinder strength

UCS Unconfined compressive strength

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