Stressed Rock Penetration Modelling and Section II/IV Testing for Shaped Charges.

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INTRODUCTION: WHY IS PENETRATION IMPORTANT

Why Perforate?

Ensure a hydraulic connection or flow passage from a hydrocarbon bearing reservoir to the wellbore.

Undamaged Rock  Skin  Perforation Tunnel

Invaded Zone
INTRODUCTION: WHY PENETRATING MODELLING?

Motivation Behind Perforation Modelling on stressed rocks:

- Well productivity is related to depth of penetration – at least exceed the drilling damaged zone (not considering near wellbore dynamics – DUB, clean-up effects etc.)
- Section II & Section IV Testing is quite time consuming and expensive
- Availability of outcrop rock or representative cores samples for ballistic testing?
- Useful tool to support experimental data on real stressed rock for optimizing rock specific charges
- Experimental error due inconsistency of natural rocks
- Limitation of test equipment to simulate down-hole conditions (HP Wells)
Drawbacks of previous penetration models used for oilfield shaped charges:

- Reliance on concrete penetration data
- Different models provide considerably different results for same shaped charge
- Tendancy to overpredict DoP in downhole environment
- Inadequate consideration of rock specific parameters – porosity, pore pressure, effective stress, limited UCS range
Thompson’s UCS Strength Model

For a given charge the penetration is logarithmically related to UCS

\[
\ln \left( \frac{D_o P}{D_o P_{ref}} \right) = 8.6 \times 10^{-5} \ (UCS_{ref} - UCS)
\]

DoP = Dop in formation (at any particular UCS)

DoP_{ref} = Dop in test formation (at reference UCS)

UCS = UCS of formation in psi

UCS_{ref} = Reference UCS of test formation

The Thompson formula does not account for stress in targets. Most shaped charges exhibit a stress dependent penetration as well as UCS dependent.
Ballistic Indicator Function Model \[\text{(SPE – 151846)}\]

combines UCS & stress function of target, including charge and target coefficients

\[
\ln \left( \frac{\text{DoP}}{\text{DoP}_{\text{ref}}} \right) = a_0 \left( F_{\text{Bl, ref}} - F_{\text{Bl}} \right)
\]

\[
F_{\text{Bl}} = \text{UCS} + b \cdot P_{\text{eff}}
\]

\[
P_{\text{eff}} = P_{c} - a \cdot P_{\text{pore}}
\]

\[
a(\varphi) = 0.0967 \varphi^{0.428}
\]

\[
b(\text{UCS}) = 0.7336 - 1.813 \times 10^{-5} \cdot \text{UCS} \quad \text{(for UCS < 30,000psi)}
\]

\[
a_0 = \text{Exponential Charge Coefficient (constant for charge design)}
\]

\[
F_{\text{Bl}} = \text{Ballistic Indicator Function of Formation (psi)}
\]

\[
F_{\text{Bl, ref}} = \text{Ballistic Indicator Function of Test Formation (10,000psi)}
\]

\[
P_{\text{eff}} = \text{Ballistic Effective Stress (psi)}
\]

\[
P_{c} = \text{Confining Stress (psi)}
\]

\[
P_{\text{pore}} = \text{Pore Pressure (psi)}
\]

\[
a = \text{Ballistic Pore Pressure Coefficient (Porosity dependent)}
\]

\[
b = \text{Stress Influence Coefficient (UCS dependent)}
\]

\[
\text{UCS} = \text{Unconfined Compressive Strength of Formation (psi)}
\]

\[
\varphi = \text{Porosity (\%)}
\]
3 x charge designs (HMX/St)

- 26g DP (Conventional)
- 26g Reactive Liner
- 6.5g DP (Conventional)

4 x sandstone rock types, range of UCS (5600psi - 11,500psi)
SANDSTONE TARGETS (7” X 30”)

Sander Schilf
~ UCS 5650psi
Porosity 19.4 – 21.5%
Perm. 120 – 170 mD

Carbon Tan
~ UCS 8900psi
Porosity 14.6 – 15.7%
Perm. 20 – 35 mD

Main
~ UCS 10150psi
Porosity 11.5 – 11.9%
Perm. 1 – 10 mD

Bunt
~ UCS 11310psi
Porosity 12.6 – 13.8%
Perm. 40 – 60 mD
Concrete Penetration vs Stressed Rock Penetration

Penetration Data vs Ballistic Indicator Function

API 19b Section I: Average Penetration in Concrete (inch)

Penetration Data vs Ballistic Indicator Function

Ballistic Indicator Function (psi)
PENETRATION MODELLING RESULTS:

Charge A: Exponential DoP Correlation for 6,5g DP HMX/St

![Graph showing the relationship between Ballistic Indicator Function (psi) and DoP/DoP_ref for 6,5g DP HMX/St. The graph includes data points and a model prediction line.]
PENETRATION MODELLING RESULTS:

**DoP Correlation with \( F_{BI} \) (incl. UCS Deviation)**

![Graph showing DoP correlation with \( F_{BI} \) and UCS deviation.](image)

**Absolute Deviation in DoP from Calculated Values (\( F_{BI} \))**

![Bar chart showing absolute deviation in DoP from calculated values.](image)
PENETRATION MODELLING RESULTS:

Charge B: Exponential DoP Correlation for 26g RL HMX/St

Ballistic Indicator Function (Psi)

DoP/DoP_{ref}

26g RL

Model Prediction
PENETRATION MODELLING RESULTS:

DoP Correlation with $F_{Bl}$ (incl. UCS Deviation)

Absolute Deviation in DoP from Calculated Values ($F_{Bl}$)
PENETRATION MODELLING RESULTS:

Charge C: Exponential DoP Correlation for 26g DP HMX/St
**PENETRATION MODELLING RESULTS:**

**DoP Correlation with F_{BI} (incl. UCS Variation)**

- Graph showing the correlation between DoP and F_{BI} with UCS variation.
- The x-axis represents Ballistic Indicator Function (Psi), ranging from 5000 to 19000.
- The y-axis represents DoP/DoP_{ref}, ranging from 0 to 1.4.
- Data points for 26g DP and model prediction are shown.

**Absolute Deviation in DoP from Calculated Values (F_{BI})**

- Graph showing the absolute deviation of F_{BI} model to actual DoP (inch).
- Deviation of 26g DP from the prediction is indicated.
- Overpredicted and Underpredicted categories are highlighted.
SUMMARY OF RESULTS

- Test results indicate that effective stress $P_{\text{eff}}$ as well as UCS has an influence on the stressed rock penetration.

- More Lab. data needed to confirm observation and also effects of $P_{\text{eff}}$ with rocks of >UCS & porosity with harder rocks.

UCS: 5700 psi
$P_{\text{eff}}$: 4600 psi

UCS: 5650 psi
$P_{\text{eff}}$: 5400 psi
SUMMARY OF RESULTS

- $F_{Bi}$ Model requires sufficient Section II data input to acquire the penetration model
- $F_{Bi}$ appears to provide a fairly accurate method of prediction for penetration depth in stressed sandstone targets – does not overpredict penetration
- Allows also for charge optimization on stressed rock using the DoP$_{ref}$ and $a_0$
- More data points required to verify higher UCS range >15,000psi for the charges tested in this program
- Accuracy of model or correlation to lab data dependent on the accuracy of the charge coefficient value and also UCS consistancy in target material
- Charge coefficient values varies with charge design (advantage of the $F_{Bi}$ Model) (Reactive Liner different to conventional DP charges)
REFERENCES


Thank you for your attention.