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SHAPED CHARGE PENETRATION INTO STRESSED ROCK

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A comprehensive experimental series was recently conducted to evaluate the penetration performance of oilwell perforating charges into stressed and unstressed Berea sandstone cores. Rock confining pressure (P_c) and pore fluid pressure (P_p) were varied from ambient to 10,000 psi, to simulate downhole stress environments typically experienced by subterranean reservoir rock.

Experiments yielded a generally inverse correlation between penetration depth and effective stress (σ_{eff}). However, a new definition of effective stress is proposed. Historically, the perforating community has defined $\sigma_{eff} = P_c - P_p$, but a new treatment ($\sigma_{eff} = P_c - \alpha P_p$; $\alpha \sim 0.6$) better fits the present data. Furthermore, this new definition of σ_{eff} better fits published historical penetration data.

This importance of static stress condition on ballistic response makes rock unique among the targets of interest to the broader ordnance community.

INTRODUCTION

Oilwell perforators are small-caliber shaped charges used to create tunnels in reservoir rock, through which hydrocarbons subsequently flow. Maximizing well productivity (defined as production flow rate divided by pressure drop) is the ultimate goal of most perforating operations. In many instances, a determinant in well productivity is the depth of the perforation tunnels. It is therefore important to understand which reservoir characteristics influence perforation depth, and to what extent.

One such characteristic is stress. Reservoir rock is subjected to overburden stress (the weight of the earth above), and associated lateral stresses. Independent of these *total stress* components, the pore fluid experiences some characteristic *reservoir pressure*, alternatively known as *pore pressure* (P_p).

In the laboratory, total stress is applied to a rock via a confining chamber, wherein pressurized liquid surrounds the elastomer-jacketed core. This stress is often termed *confining stress* or *confining pressure* (P_c). In many laboratory scenarios, confining stress is isotropic, even though real reservoirs are seldom isotropic. Pore fluid is pressurized by a dedicated pump and associated plumbing, independent of the confining fluid system.

We recently conducted an extensive experimental series, wherein we shot several charges into outcrop Berea sandstone targets, subjected to varying combinations of confining and pore pressures. This enabled the identification of rock stress parameters of importance, and the development of meaningful correlations between these parameters and penetration depth for this standard target.

Rock Mechanics Considerations

In classical geomechanics analyses [1], *effective stress* (σ_{eff}) is a quantity of fundamental importance. This is a general measure of the net stress experienced by the solid matrix.

Quasi-static failure behavoir of rocks, and deformation behavoir of soils, are governed by $\sigma_{eff} = P_c - P_p$, whereas rock deformation is instead governed by $\sigma_{eff} = P_c - \alpha P_p$ ($0 \leq \alpha \leq 1$). The pore pressure multiplier (α) – commonly known as Biot’s constant – is an intrinsic rock property which can be determined by different methods [1,2]. This parameter is very strictly defined within the framework of poroelasticity theory; it is not merely an empirical “fudge factor”.

Over a broad range of rocks, Biot’s constant is found to generally trend with porosity and permeability, ranging from low values for tight rocks toward unity for high-porosity high-permeability rocks. Furthermore, this quantity may not be, in the most general sense, a constant. For example, ref. [2] reports that Berea’s poroelastic parameter α can range from 0.6 to 0.85, depending on the particular sample and determination method used. Ref. [2] also reports a slight stress dependency, where α varies inversely with confining stress. As with other rock mechanical properties, α is typically determined under quasi-static loading conditions.

Penetration Correlations

The oilfield industry has long recognized an inverse relationship between rock stress and shaped charge penetration depth [3,4]. Since the 1980’s, predictive models have related penetration to the simpler definition of effective stress ($\sigma_{eff} = P_c - P_p$).

The present work is an attempt to re-visit this basic assumption – to explore whether pore pressure has an absolute effect not previously recognized. In other words, the current effort addresses the question: *might* $\alpha \neq 1$ *better predict penetration performance?*

If *yes*, it is important to note that the thus-inferred value for α is claimed to be applicable to ballistic penetration, but not necessarily to other rock mechanics phenomena. Any value for α determined in this present work is not intended to supplant recognized values for Biot's constant relevant to traditional rock mechanics analyses. That said, arguments might be advanced which predict a concurrence of the ballistic pore-pressure multiplier and traditional published values for Biot's constant.

EXPERIMENTS

Setup

A purpose-built test vessel (Fig. 1) is capable of subjecting a target rock sample to independent static confining stresses and pore fluid pressure, up to 10,000 psi. This allows the laboratory creation of stress states comparable to those experienced by "normal" reservoirs buried up to 10,000 feet below ground level. While this vessel replicates downhole rock stress, it does not replicate downhole temperature or wellbore fluid pressure. This trade-off of features makes the vessel an economically viable tool to evaluate the effects of rock stress (and other characteristics) on shaped charge penetration depth.

For the present effort, several commercial perforating charges (of a single design) were shot into outcrop Berea sandstone cores, at different combinations of (isotropic) confining stress and pore pressure. Berea is a commonly used laboratory rock within the petroleum industry, particularly for perforating studies. It is a fine- to medium-grained sandstone, with an unconfined compressive strength (UCS) of approximately 8000 psi, porosity of 20%, and permeability of 200 millidarcies.

For all tests, pore fluid was 3% potassium chloride brine. This is a standard saturating fluid, more convenient to handle than petroleum-based liquids for such laboratory studies. At a minimum, two charges were fired at each stress condition. All charges were selected from the same box of a single production run.

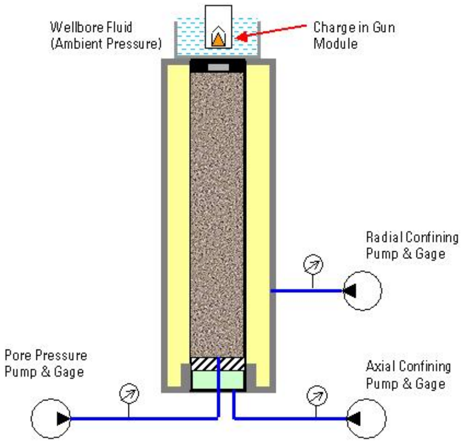

Figure 1. Pressure vessel schematic

Results & Discussion

Figure 2 shows normalized penetration depth results, plotted against the historical definition of effective stress ($\sigma_{eff} = P_c - P_p$). The dashed curve is an exponential fit of the ambient pore pressure data. The exponential form was selected based on inspection of the data, and the fitting parameters were chosen to make the curve reasonably fit the data. The precise form of this reference curve is not germane to the following analysis; it is placed on the chart solely to facilitate qualitative assessment of how well the various elevated pore pressure data collapse onto a universal curve.

In cases where pore pressure was low compared to confining stress, the traditional effective stress definition is a good indicator of penetration depth (i.e. the data lie near the reference curve). High pore pressure data, however, lie significantly below the reference curve. These more extreme cases reveal that pore pressure does in fact exhibit some absolute effect that had not been previously recognized. Put differently: a unit increase in pore pressure does not completely negate a unit increase in confining stress. This suggests the existence of an improved effective stress definition – one which weights the pore pressure effect accordingly.

Figure 3 shows the same penetration data, but plotted against a modified definition of effective stress ($\sigma_{eff} = P_c - \alpha P_p$). In Figure 3, $\alpha=0.6$ was chosen by inspection, to make all elevated pore pressure data better collapse onto the reference curve. This process yielded qualitatively-equivalent “goodness of fit” for $0.5<\alpha<0.7$;

although values of α at the low end of this range slightly improved the fit the highest pore pressure data, while slightly worsening the fit of the intermediate pore pressure data. The resulting data scatter in the elevated pore pressure data is consistent with the scatter in the ambient pore pressure data. As was the case when selecting the exponential curve to approximate the ambient pore pressure data, no attempt was made here to employ rigorous statistical methods to identify the precise optimum value for α.

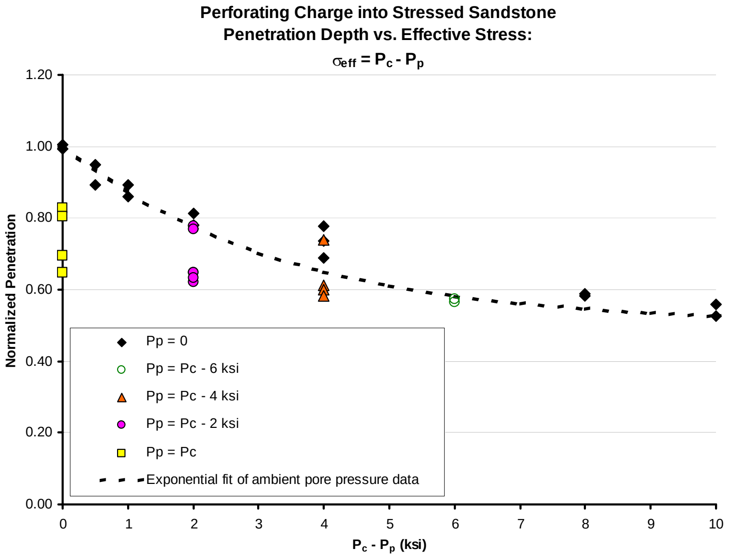

Figure 2. Penetration depth into rock; historical definition of effective stress

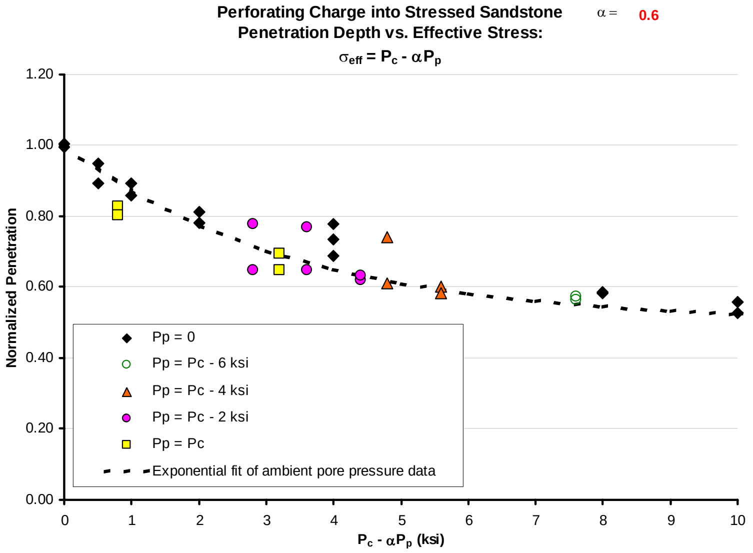

Figure 3. Penetration depth into rock; improved definition of effective stress

Comparison With Historical Data

It is worth re-visiting historical data [3] in the context of these recent findings. Figure 4 shows penetration depth plotted against (P_c - P_p), for the data taken from ref. [3]. Figure 5 shows this same penetration data, but vs. (σ_{eff} = P_c - αP_p,; α=0.6). As with the current data, this historical penetration data better fit the new effective stress definition.

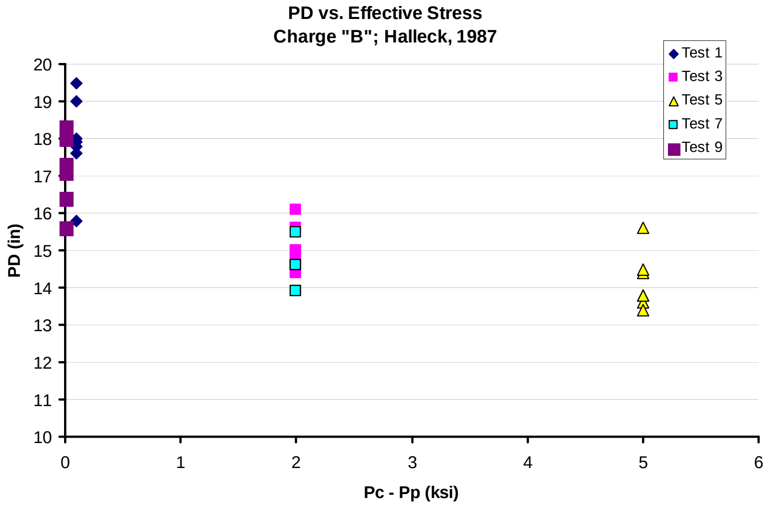

Figure 4. Penetration depth into rock [3]; traditional definition of effective stress

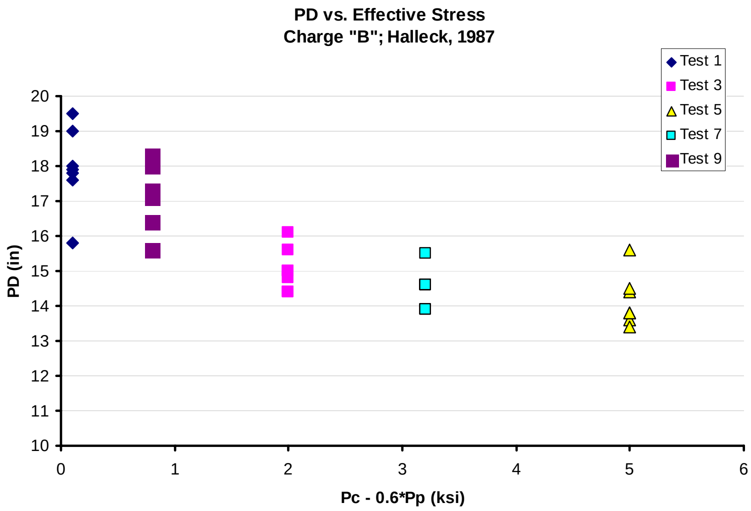

Figure 5. Penetration depth into rock [3]; improved definition of effective stress

CONCLUSIONS & RECOMMENDATIONS

Recent experiments yielded an inverse correlation between shaped charge penetration depth and effective stress for Berea sandstone, in general agreement with previous experience. However, a new definition of effective stress is proposed. Historically, the industry has defined $\sigma_{eff} = P_c - P_p$, but a new definition ($\sigma_{eff} = P_c - \alpha P_p$; $\alpha<1$) better fits the present data. Specifically, for the present work, $\alpha=0.6$ gives a reasonable fit to all data collected. Furthermore, this new definition of σ_{eff} better fits published historical results.

That two completely different bodies of experimental data – collected two decades apart and involving different generations of perforating charges and different experimental facilities – yielded virtually identical values of α, suggests that this is indeed a fundamental rock characteristic important to shaped charge penetration. It further suggests that *the representative value* for α in Berea sandstone lies in the range 0.5-0.7, and is fairly insensitive to the particular sample of Berea used (as the two experimental efforts involved different samples from potentially different quarries).

Our inferred pore pressure multiplier is within the range of published values of Berea's poroelastic constant ($0.6 < \alpha < 0.85$) [2]. Reasons for this concurrence are being investigated, as part of a broader effort to introduce classical poroelasticity theory into the analysis of shaped charge penetration.

Being a fundamental rock property, α is expected to vary among different rocks. Indeed, determination of appropriate values of α for other geomaterials is the subject of the authors' ongoing research.

These findings, and those that will follow, are important to the petroleum industry's ongoing pursuit of more accurate penetration models. Improvements in understanding of shaped charge penetration, and the implementation of this improved understanding into predictive models, should enhance our ability to reliably predict the ultimate deliverability of hydrocarbon reservoirs.

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