A New Perspective in Hydrofracture Analysis

By: Stefan Goerz, M.Sc., P.Eng, P.E, CCI Inc.,
Nicolas Boelhouwer, P.Geo, CCI Inc.,
Justin Taylor, P.Eng, P.E, CCI & Associates Inc.

1. OVERVIEW

Most critical Horizontal Directional Drilling (HDD) projects in North America continuously monitor drilling fluid annular pressure during construction for mitigating risk of inadvertent returns (IR) of drilling fluids to the surface or to waterbodies (which is also sometimes called hydrofracture, or "frac out"). Downhole tooling automatically records "real-time", or "as-built" pressure data throughout the length of the HDD crossing and relays it back to the driller. While this data is extremely important during the construction of an HDD, the data is also useful to determine whether the theoretical drilling fluid and confining pressure calculations used by the HDD designer are valid. This article will give readers an insight into recent findings which show how the measured data compares to the industry standard calculated values.

To begin, the authors collected this as-built annular pressure data from past HDDs and compared it to the calculated theoretical drilling fluid pressure within the annulus of the borehole. Results of this analysis show the accepted drilling fluid models (in particular, the Bingham Plastic model) used to calculate the annular pressure during drilling generally compare well to the data obtained.

Although the accepted models accurately predict actual fluid pressure downhole, the accurate prediction of confining pressure (ie hydraulic fracture) is a different story. In order to assess the accuracy of the confining pressure calculations the authors have used as-built annular pressure data to determine the date, time, and pressure magnitude of actual hydraulic fracture occurrences in HDD crossings. Through careful evaluation, these occurrences have been isolated within the as-built data and compared to the predicted hydraulic fracture pressure calculated by the industry-standard "Delft" equation using site specific geotechnical parameters.

Results of the analysis of as-built data show that in most, if not all cases the "Delft" solution over-predicts the actual hydraulic fracture pressure, which can lead to severely unconservative designs and fluid release issues during construction. Additionally, the suggested factors for the "Delft" equation variable $R_{p,max}$ of 1/2 and 2/3 multiplied by the overburden height for clay and sand, respectively, have not been previously investigated and compared to actual hydraulic fracture data. Contained within this research, the $R_{p,max}$ value is modified to determine at what value the Delft equation best predicts the actual hydraulic fracture pressure.

2. A BRIEF INTRODUCTION TO HYDROFRACTURE EVALUATION

Hydrofracture / Inadvertent Return evaluation during HDD construction has increasingly become a more significant stage of engineering design. Typically, a hydrofracture evaluation includes a comparison analysis of the expected drilling fluid pressures (see Section 3 below), and the expected confining or "frac-out" pressure (see Section 4 below). These are two exclusive parts of the evaluation. However, the underlying principle is that the expected fluid pressure should be maintained below the soil confining pressure (in other words the pressure of the fluid in the borehole should be less than the earth pressure pushing back on the borehole walls), otherwise hydraulic fracture may occur.

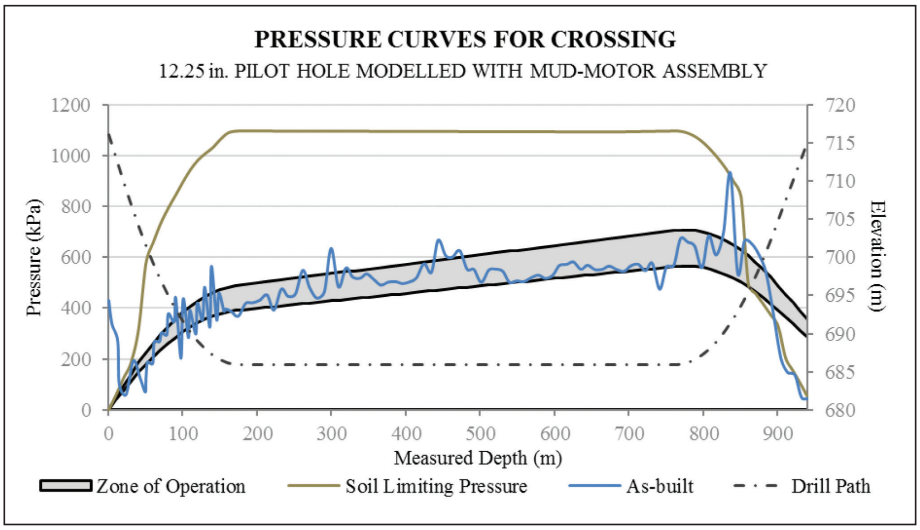

Figure 1: Example of as-built data overlain on the annular pressure model and design calculations

$$P'_{max} = [\sigma'_0(1+\sin\varphi) + c\cos\varphi + c\cot\varphi]\left[\left(\frac{R_0}{R_{p,max}}\right)^2 + \frac{(\sigma'_0\cdot\sin\varphi + c\cdot\cos\varphi)}{G}\right]^{\frac{-\sin\varphi}{(1+\sin\varphi)}} - c\cot\varphi \quad [1]$$

Where:

σ'_0 =	Effective Stress [kPa]
φ =	Effective Angle of Internal Friction [degrees]
c =	Cohesion [kPa]
R_0 =	Initial Hole Radius [m]
R_g =	Hole Radius [m]
$R_{p,max}$ =	Maximum Plastic Radius [m]
G =	Shear Modulus [kPa]
P'_{max} =	Maximum Allowable Pressure [kPa]

(1) The 1988 Delft Equation used to predict hydrofracture pressure

3. DRILLING FLUID PRESSURES DATA ANALYSIS AND COMPARISON

There are various models designers and contractors may use to estimate the fluid pressures during HDD construction, however the Bingham-Plastic Non-Newtonian fluid model is the most common and has been used for this analysis.

Over 50 HDD projects with recorded annular pressure analysis data have been evaluated by use of spreadsheet tools developed by the authors. Following extensive analysis of each as-built data set obtained, the organized data was overlain on the HDD design annular pressure chart calculated during the design stage.

The example chart shown in Figure 1 demonstrates the result when the average as-built pressures are overlain on the design annular pressure calculation chart. The two solid black lines and grey shading represent the "Zone of Operation" of which the base line is the calculated drilling fluid pressure and the upper line is a 1.25 times factor multiplier on the design calculation. The 1.25 times factor is intended to account for field variation in fluid parameters during construction that may be different from the design stage and allow an acceptable tolerance for the operator. The green solid line represents the "Soil Limiting Pressure" which is the calculated pressure threshold the soil surrounding the HDD path is anticipated to withstand before a hydrofracture is induced. This is discussed in greater detail in Section 4. In an ideal fit, the as-built data tracks entirely within the upper bound of the zone of operation. In the example above, the fluid pressures (blue line "As-built") are mostly maintained throughout the crossing, however there is evidence of a few high-pressure events.

In general, the data compares well with the model used during the design phase. Based on actual measured pressures during construction, we can see that the Bingham Plastic model typically used in these design calculations is suitably accurate.

4. CONFINING PRESSURE DATA ANALYSIS AND COMPARISON

The most common method to predict the hydrofracture pressure is the well-known "Delft" equation which was first developed for use in HDD construction by Luger and Hergarden, in 1988. The Delft equation [1] is shown at the top of this page.

As shown in equation [1], a very important parameter within the equation is the value of the maximum plastic radius ($R_{p,max}$). This value is considered the extent of the yielding soil material around the borehole at the maximum allowable pressure. Additionally, it has been assumed that if this radius extends to the topographic surface, hydrofracture will occur. Commonly, $R_{p,max}$ is taken as the height of the soil above the HDD path multiplied by factors of 1/2 and 2/3, for clay and sand, respectively. Notably, these factors for $R_{p,max}$ have been adopted for use in hydrofracture calculations by the United States Army Corps of Engineers (USACE) through the publication of the Construction Productivity Advancement Research Program report CPAR-GL-98-1, *"Installation of Pipelines Beneath Levees Using Horizontal Directional Drilling"*. These factors and their common use in USACE-sanctioned HDD projects provide the basis for comparison.

4.1. METHODS

For select HDD construction projects where hydraulic fracture has occurred, the as-built annular pressure data, in combination with HDD construction inspection reports, are used to determine the date, time, and pressure magnitude of actual hydraulic fracture occurrences in HDD crossings. These pressure magnitudes can be used to evaluate the design calculation, and as used in this research, evaluate the size of the maximum plastic radius.

To identify a hydraulic fracture within the data, the largest as-built pressure before the release is observed on surface, should be taken as the fracture pressure. Often the data will show a distinct trend as shown on the chart in Figure 2, on page following.

In most cases the entire fracture characteristic curve is not observed, and only the "breakdown" and "fracture propagation" pressures are present. Generally, the pressures are monitored

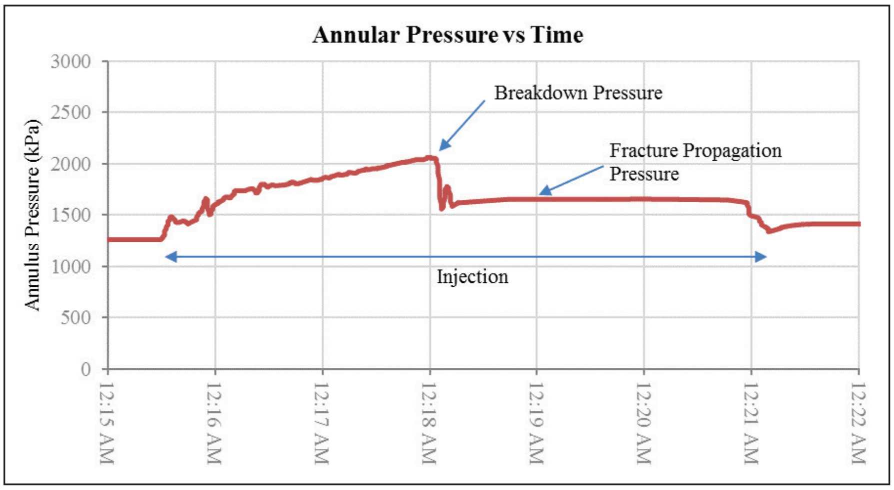

Figure 2: Hydraulic fracture characteristic curve. During the injection phase, drilling fluid is introduced into the borehole through the drill bit

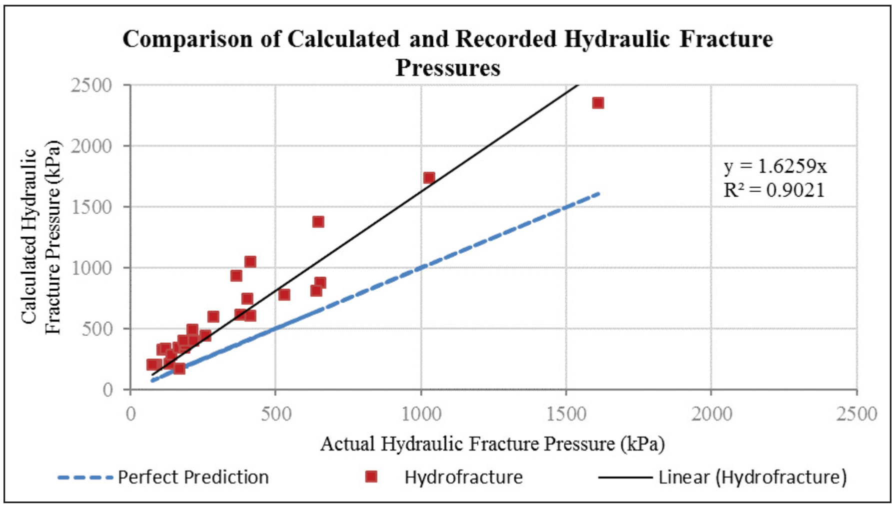

Figure 3: Calculated hydraulic fracture pressure as a function of measured hydraulic fracture pressure

very closely and immediately after viewing abnormally high pressures during construction, the operator stops to evaluate the situation.

4.2. COMPARISON OF CALCULATED AND AS-BUILT HYDROFRACTURE PRESSURES

Using the pressure magnitude of over 30 hydraulic fracture occurrences, the as-built pressure could be compared to the theoretical confining pressure values. The chart shown in Figure 3, above, demonstrates the differences between calculated hydraulic fracture pressures using $R_{p,max}$ factors of 1⁄2 and 2⁄3 for clay and sand, respectively, and as-built hydraulic fracture pressures.

As shown on the chart above, the calculated pressure line of best fit is sloped greater than one to one (Perfect Prediction). This suggests that the calculated theoretical fracture pressure is generally larger than the actual measured as-built fracture pressure and is therefore considered unconservative. This analysis shows that, for the data obtained, the Delft equation predicts hydraulic fractures consistently at a value of 1.6 times the actual hydraulic fracture pressure.

4.3. ACTUAL $R_{P,MAX}$ COMPARISON

After extensive review of the as-built fracture pressure data, the maximum plastic radius ($R_{p,max}$) was back-calculated using the Delft equation in order to obtain the actual radius of the plastic zone at hydrofracture failure.

The chart shown in Figure 4, on page following, shows the back-calculated plastic radius at failure for the data obtained from previously published experimental work, and actual HDD projects.

As shown in Figure 4, the data suggests that the maximum plastic radius at failure likely doesn't extend to surface for hydraulic fracture to occur. In fact, the recommended 2⁄3 and 1⁄2 factors placed on the height of the overburden also overestimate the extent of the plastic zone. This overestimate becomes more evident as the bore path gains depth. Additionally, there is no apparent linear correlation to conclude that the depth of the HDD alignment has large influence on plastic zone development. A reduction of the maximum plastic radius to a value more localized around the pilot borehole, as suggested by the research completed herein, reduces the maximum allowable pressure as calculated by the Delft equation.

5. CONCLUSIONS AND RECOMMENDATIONS

The first part of this research investigated the comparison between recorded fluid pressure and the calculated fluid pressure at the design stage. Generally, the data compares well with the prediction using a modified Bingham Plastic model.

In the second part of the research, the data analysis provided a basis for examining actual hydraulic fracture pressures and comparing the values to the prediction using the Delft method. Additionally, the maximum plastic radius was back calculated and the values were assessed. According to the data obtained, the values of actual fracture pressure were overestimated by the calculation, when the suggested maximum plastic radius values were used. When the values of the maximum plastic radius were back calculated, the data suggests that the values are substantially lower than as suggested, and there is no apparent correlation to depth of cover. By using a much lower, more localized plastic radius the calculated hydraulic fracture pressure becomes more comparable to the actual hydraulic fracture pressure.

Hydrofracture during HDD is one of the construction method's most prominent issues, and requires careful bore design, construction planning and monitoring in order to effectively manage the risk of severe environmental consequences and property damage that may occur. The reduction in maximum allowable pressure suggested by this research provides a more conservative HDD design, and will lead to much less inadvertent return events on trenchless projects. Reduction of inadvertent fluid release is not only important to the success of a particular HDD project, but also in maintaining a positive image for the entire HDD industry.

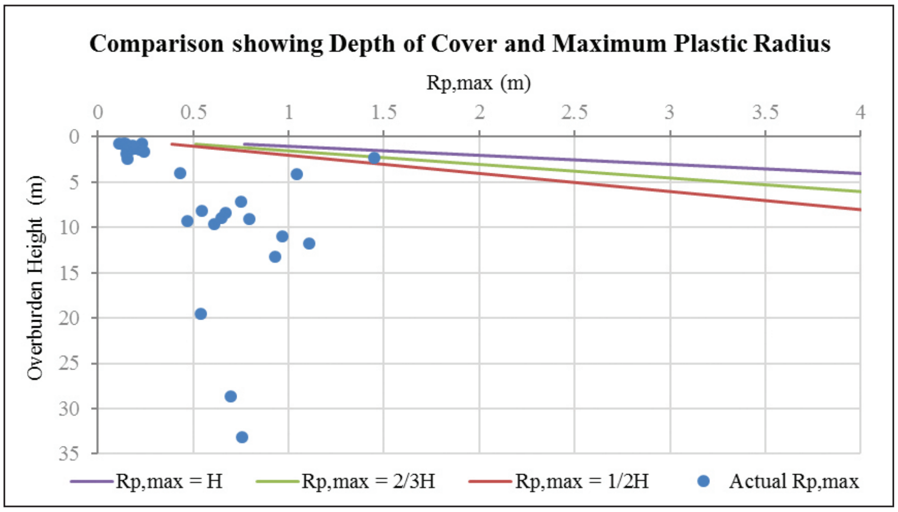

Figure 4: Plastic radius at failure as a function of overburden height

ABOUT THE AUTHORS:

Stefan Goerz, M.Sc., P.Eng, P.E., has over seven years of experience as a geotechnical engineer with CCI Inc., based in Alberta, Canada in the field and office delineating subsurface conditions and providing recommendations for a variety of trenchless pipeline projects.

Nicolas Boelhouwer, P. Geo, is a Geologist for CCI Inc. working out of Alberta, Canada and has seven years of experience helping to develop successfully engineered trenchless installations.

Justin Taylor, P.Eng, P.E is the VP of Engineering for CCI & Associates Inc., based out of Houston, TX, and has over 13 years of trenchless experience, focusing on HDD and Direct Pipe installations.