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EFFECTIVENESS OF HYDROFRACTURE PREDICTION FOR HDD DESIGN

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ABSTRACT: Mitigation against the risk of hydrofracture is an essential part of horizontal directional drill (HDD) design. Previous studies have developed methods to evaluate hydrofracture risk based on soil and fluid mechanics properties, including cavity expansion theory (Luger and Hergarden, 1988; Bennett and Wallin, 2008; Ariaratnam et al., 2003; Staheli et al., 1998). While these studies have been instrumental in the area of hydrofracture risk analysis, there is currently little comparison of field observed bore pressures and the theoretical predictions generated through these methods. This paper investigates the cavity expansion theory and reports the results of a critical analysis of the factors that impact the calculated limiting pressures for hydrofracture. Comparisons are then made between the theoretical calculations for maximum bore pressure and actual bore pressure observed on different HDD projects where hydrofracture occurred, characterizing the effectiveness of the method, and furthering the accuracy of hydrofracture prediction for future HDD designs.

1. INTRODUCTION

The risk of hydrofracture is a consideration on most major horizontal directional drilling (HDD) projects. Within the last 10 years, there has been a concerted effort within the HDD community to quantify limiting down-hole fluid pressures which will cause hydraulic fracturing of the soils, possibly resulting in inadvertent drilling fluid returns at the ground surface. Many have evaluated and used the cavity expansion model (Luger and Hergarden, 1988) to determine the maximum down-hole fluid pressures and to determine appropriate drilling depths beneath critical project elements such as rivers or wetlands. Others have suggested the use of the total stress model to determine maximum drilling pressures. Although the merits of each method have been argued, insufficient data have been collected on HDD projects comparing the actual down-hole fluid pressures at locations of inadvertent fluid returns to the model predictions. This is largely because down-hole pressure measurements have only been collected on HDD utility projects in the recent past. As more data are collected and compared to prediction models, adjustments can be made to the assumptions that feed each model, resulting in more accurate hydrofracture predictions. In order to understand the comparison between estimated hydrofracture pressures and actual down-hole pressures that cause inadvertent returns, it is first necessary to examine the equations used to predict limiting drilling fluid pressures and the parameters that have the most effect on the predictions.

2. CAVITY EXPANSION THEORY

Cavity expansion theory was first applied to HDD bores by Luger and Hergarden in 1988. The cavity expansion model and its application to HDD are described in detail in Bennett and Wallin (2008). The model is developed to establish the maximum allowable pressure that can be applied to a given soil without hydrofracture occuring. This maximum allowable pressure is expressed as the following:

$$p_{max} = u + [\sigma_0' \cdot (1 + \sin\varphi) + c \cdot \cos\varphi + c \cdot \cot\varphi] \cdot \left(\left(\frac{R_0}{R_{pmax}} \right)^2 + \frac{\sigma_0' \cdot \sin\varphi + c \cdot \cos\varphi}{G} \right)^{\frac{-\sin\varphi}{1+\sin\varphi}} - c \cdot \cot\varphi \quad [1]$$

Where:

$p_{max} =$ Maximum Allowable Mud Pressure $\left[\frac{lb}{ft^2}\right]$

$R_0 =$ Bore Radius $[ft]$

$R_{pmax} =$ Radius of the Plastic Zone $[ft]$

Variables Dependent on the Soil:

$\varphi =$ Soil Friction Angle [°]

$c =$ cohesion $\left[\frac{lb}{ft^2}\right]$

$G =$ Shear Modulus $\left[\frac{lb}{ft^2}\right]$

$\gamma =$ Unit weight of soil above the groundwater $\left[\frac{lb}{ft^3}\right]$

$\gamma' =$ Unit weight of soil below the groundwater $= \gamma - \gamma_w$ $\left[\frac{lb}{ft^3}\right]$

Variables Dependent on Bore Geometry:

$h_s =$ Depth of the Bore below Ground Surface $[ft]$

$h_w =$ Height of groundwater over the bore $[ft]$

$u =$ Groundwater Pressure $= \left|\frac{lb}{ft^2}\right|$

$\sigma' =$ Effective Stress $= \gamma \cdot (h_s - h_w) + \gamma'(h_w) \left|\frac{lb}{ft^2}\right|$ (2)

The value for the radius of the plastic zone (R_{pmax}) is established by the user. When trying to establish the pressure at which hydrofracture will occur, the value for the radius of the plastic zone is typically set to the ground surface elevation. During design, a factor of safety is commonly applied to the radius of the plastic zone to ensure that the plastic zone does not reach the surface. Safety factor values of 1.5 are usual for sands while values of 2.0 are applied for clays (Delft, 1997; Bennett and Wallin, 2008).

A. Sensitivity Analysis for the Cavity Expansion Model

When using the cavity expansion theory, it is important to understand how the independent variables within the equation impact the overall calculation of the limiting pressure. To this end, a sensitivity analysis of each variable was conducted to establish this relative impact. For this analysis, each variable was analyzed over a range of values that would be typical for that particular parameter. Table 1 shows the parameters that were analyzed and the range of values over which the analysis was conducted.

Table 1. Parameters Used in Sensitivity Analysis for Cavity Expansion Theory

Parameter	Low	←	→		High	Mean
$h_s\ [ft]$	10	20	30	40	50	30
$h_w\ [ft]$	0	12.5	25	37.5	50	25
$R_0\ [ft]$	0.25	0.375	0.5	0.625	0.75	0.5
$c\ \left[\frac{lb}{ft^2}\right]$	0	400	800	1200	1600	800
$\gamma\ \left[\frac{lb}{ft^3}\right]$	90	100	110	120	130	110
$\varphi\ [°]$	24	26	28	30	32	28
$G\ \left[\frac{lb}{ft^2}\right]$	17,800	468,400	918,900	1,369,500	1,820,000	918,900
$R_{pmax}\ [ft]$	10	20	30	40	50	30

The maximum allowable pressure was calculated using the mean value for each of the input parameters resulting in a pressure of 244 psi. Each of the input parameters was systematically varied from low to high while holding all other parameters constant at the mean value. The results of the analysis are presented in the tornado diagram shown in Figure 1. As one would expect, the parameter that has the greatest influence on the maximum allowable pressure is the depth of the bore (h_s).

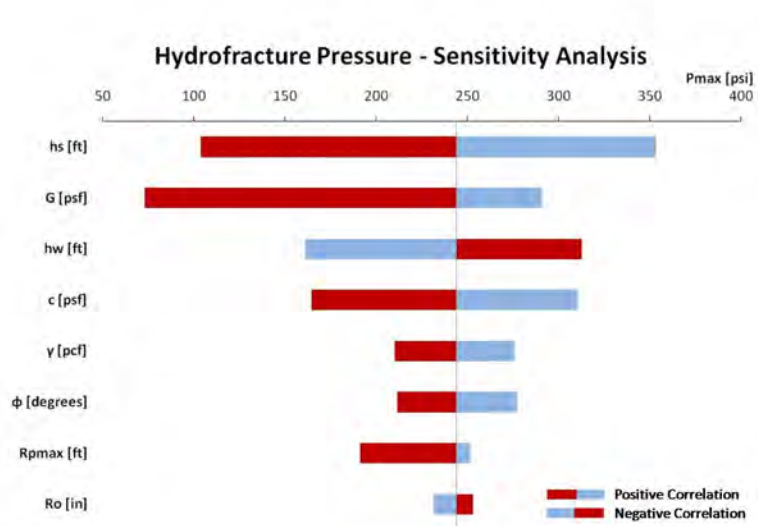


Figure 1. Sensitivity Analysis Results on Cavity Expansion Model for P_{max}

B. The Impact of Shear Modulus on the Cavity Expansion Model

What is not immediately obvious from inspection of the maximum pressure equation is the influence of the shear modulus, G. Figure 1 shows that there is a strong positive correlation between the shear modulus and the maximum pressure, that is, as the shear modulus increases, the value of the maximum pressure increases. The shear modulus G is defined as:

$$G = \frac{E}{2\cdot(1+\nu)} \quad \left[\frac{lb}{ft^2}\right] \qquad (3)$$

Where:

$E =$ Elastic Modulus $\left[\frac{lb}{ft^2}\right]$

$\nu =$ Poisson's Ratio $[-]$

The strong dependence on the shear modulus is of particular interest because the accurate determination of the soil shear modulus is difficult and not well understood. In addition, the shear modulus is rarely provided in a standard geotechnical report, making an appropriate selection of shear modulus very difficult for the average geotechnical engineer. The Shear Modulus is calculated from E and ν [3]. Some references for the elastic modulus of various soils do exist. For example, the US Army Corps of Engineers provides recommendations for values for the elastic modulus as shown in Table 2.

Table 2. Values of Elastic Moduli from USACE EM 1110-1-1904

Soil Type	**Elastic Modulus [tsf]**
Very Soft Clay	5-50
Soft Clay	20-200
Medium Clay	200-500
Stiff Clay, Silty Clay	500-1000
Sandy Clay	250-2000
Clay Shale	1000-2000
Loose Sand	100-250
Dense Sand	250-1000
Dense Sand and Gravel	1000-2000
Silty Sand	250-2000

In addition, the Poisson's ratio of a soil is not easy to determine with the standard field and or laboratory testing that is typically performed for HDD projects. Values of typical Poisson's ratios are provided for a number of soils. Table 3 provides suggested values of Poisson's ratio, , from the Geotechnical and Geoenvironmental Engineering Handbook (Rowe, 2000).

Table 3. Values of Poisson's Ratio by Rowe (2000)

Soil Type	**Poisson's Ratio, , [in/in]**
Saturated Soil, Undrained Loading	0.5
Clay, Drained Loading	0.2-0.4
Dense Sand, Drained Loading	0.3-0.4
Loose Sand, Drained Loading	0.1-0.3
Peat, Drained Loading	0.0-0.1

Table 2 reveals the wide range over which the elastic modulus of the soil fluctuates for a single soil type. Table 3 also shows the variation of Poisson's ratio for a particular soil type. Due to the large range of values associated with both the elastic modulus and Poisson's ratio for any given soil, it is apparent that the Shear Modulus would consequently be as widely varied and hard to determine with any degree of certainty. This variability, in turn, has a marked impact on the calculated value of the maximum pressure using the cavity expansion model.

2C. The Impact of Groundwater on the Cavity Expansion Model

Another interesting finding from the sensitivity analysis was the overall effect of the groundwater on the maximum drilling fluid pressure. From the tornado diagram, one can see that the height of groundwater over the pipeline is the third most influential parameter in the maximum pressure calculation. Cursory examination of the cavity expansion equation might suggest that the limiting pressure fluctuates directly with the groundwater pressure. As a result, one might conclude that elevated groundwater pressure reduces hydrofracture risk because it counterbalances drilling fluid pressures. However, the groundwater level has a significant impact on the effective stress (Equation 2) which, in turn, has a significant effect on Equation [1]. The influence of the effective stress in Equation [1] is far greater than the groundwater pressure, u, therefore, it may be more appropriate to view the correlation in terms of the effective stress: as the effective stress decreases (the groundwater increases), the maximum pressure decreases. As a result, Figure 1 shows a negative correlation between the maximum pressure and the height of water above the bore, i.e. as the groundwater level increases, the limiting pressure decreases. This can be seen in Figure 2 which shows the fluctuations in limiting pressure as a function of groundwater level while all other parameters in the cavity expansion model are held constant.

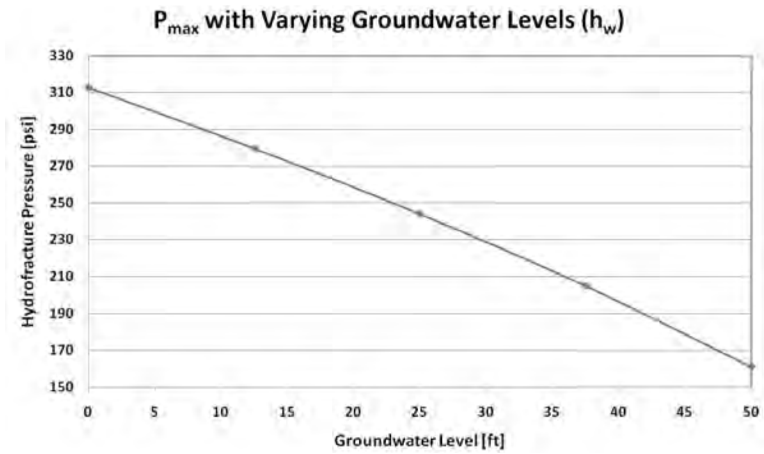


Figure 2. Effects of Changes in Groundwater Level on P_{max}

From Figure 1 it can be seen that both the groundwater level and the bore radius are inversely correlated with maximum pressure. All other input parameters are positively correlated: as the parameter increases in value, the maximum pressure increases in value.

2D. The Influence of R_{pmax} on the Cavity Expansion Model

Perhaps the most significant finding from the sensitivity analysis is the influence of the radius of the plastic zone R_{pmax} on the maximum pressure calculation. By setting the R_{pmax} to the elevation of the ground surface, a maximum pressure can be calculated that would ensure that inadvertent returns would occur at ground surface. It has been suggested that the radius of the plastic zone should be the value that designers use to establish a safe distance from critical elements such as a river or the ground surface when trying to protect against inadvertent returns. (Delft, 1997) For example, applying a safety factor of 1.5 for sands or 2.0 for clays could be used to determine the maximum pressure at the critical location (Delft, 1997),

However, analysis of the cavity expansion model shows that changes in the value of R_{pmax} only affect the value of the calculated maximum pressure within a very small radius of the bore, suggesting that the plastic zone is localized and of finite size. Once the plastic zone increases from the borehole a short distance (on the order of 2-3 bore hole diameters), changes in the value of R_{pmax} have a negligible effect on the calculated maximum pressure.

Table 4 shows soil parameters and bore geometry for a bore that is 70 feet deep with 25 feet of groundwater above the bore. The soil is representative of hard sandy silt. Table 4 also presents the variation in the calculated maximum pressure over a range of values for R_{pmax} . This relationship clearly indicates that any factor of safety applied to the cavity expansion model should **not** be applied to the R_{pmax} value as it has little to no effect on the calculated maximum pressure at distances more than a few feet from the bore.

Table 4. Variation in Maximum Pressure with changes in R_{pmax}

Input Values	
h_s [ft] = 70	φ [degrees] = 30
h_w [ft] = 25	E [tsf] = 250
R_0 [in] = 6	ν [in/in] = 0.35
c [psf] = 500	G [psf] = 185,000 (calculated)
γ [pcf] = 110	

R_{pmax} [feet]	*Maximum Pressure [psi]
10	294.7
20	302.6
30	304.2
40	304.7
50	305
60	305.1
70 (Ground Surface)	305.2

* Significant figures included illustrating the small changes in bore pressure with large changes in R_{pmax}

Of interest is the change in maximum pressure within close proximity of the borehole. Figure 3 shows how the maximum pressure varies within a few feet of the borehole. The figure shows that it takes a significant amount of pressure to increase the plastic zone around the bore but that the pressure will plateau to a maximum value.

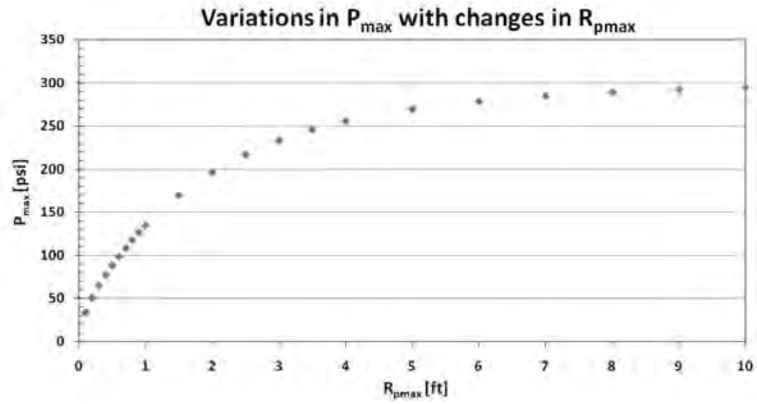


Figure 3. Changes in Maximum Pressure with Changes in the Radius of the Plastic Zone within Close Proximity of the Borehole

For the bore location represented by the parameters in Table 4, Figure 3 suggests that once the radius of the plastic zone increases to a particular point that is relatively close to the bore, within ten feet, the value of R_{pmax} has virtually no effect on the calculated maximum pressure. Some have suggested that in design a factor of safety is typically applied to R_{pmax} to prevent the plastic zone from reaching the ground surface and that the factor of safety should be commensurate with the potential consequences and the reliability of the input parameter value used in the analysis (Bennett and Wallin, 2008). However, it is clear from the evaluation of Figure 3 that using a factor of safety to reduce R_{pmax} from a value that represents the ground surface will have little impact on the calculated maximum pressure and therefore should not be used as a means of achieving conservative results. Instead, a factor of safety should be applied to the calculated maximum pressure.

3. DOWNHOLE PRESSURE MEASUREMENTS AND FIELD DATA

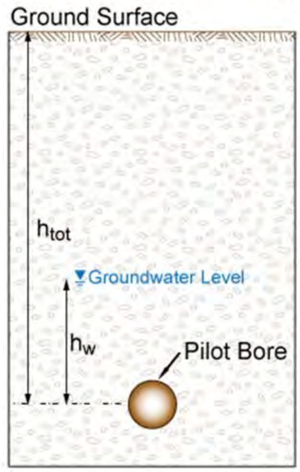
On two recent projects, Staheli Trenchless Consultants provided on site construction risk management services, monitoring the contractor's actions, drilling parameters, and performing time-in-motion studies to provide information to the Owner with respect to real-time evaluation of drilling progress and the nature of any challenges that arose during drilling operations. On these projects, down-hole pressure monitoring was performed by including a pressure transducer in the drill string, approximately 25 feet behind the drill bit. The pressure sensor was hard-wired through the drill pipe and provided information to the locator on the same computer used for the tracking system. The real-time pressure readout was available to the driller and also logged. The data were provided to the construction risk manager on a daily basis at the completion of drilling.

When drilling the pilot bore on these projects, inadvertent returns occurred at two locations with dramatically different conditions, i.e. soils, depths, groundwater level, etc. Each of these locations were captured on the down-hole pressure monitor and significant increases in pressure could be seen at the inadvertent return locations.

A. Location 1

The first site for analysis was an HDD that was constructed in hard to very hard silt with sand. The depth of the bore at the location of the inadvertent return was 70 feet. The geotechnical report provided measured values for the unit weight of the soil and the friction angle. The groundwater elevation was measured within standpipe piezometers that were installed at the site during the geotechnical investigation. The values for cohesion, Poisson's ration, and the elastic modulus were estimated and are shown in Figure 4.

Location 1



Parameters	Values
h_s	70 ft
h_w	25 ft
R_0	6 in
γ	125 pcf
ϕ	30°
c	500 psf
ν	0.35
E	250 tsf
G	185,000 psf

Figure 4. Location 1 - Geometry and Soil Parameters

While drilling the pilot bore, the drilling operations progressed very quickly and at times were drilling at a rate that was "out running the pumps" in comparison to the theoretical volume of mud that should have been pumped to adequately clean the borehole. The pilot drilling was performed with a down-hole mud motor to increase drilling rates. Down-hole pressures were relatively low except during borehole collapse. During these times, the down-hole pressure sensor would record significant and immediate spikes in pressure that would only dissipate when the blockage along the bore path was cleared or when drilling stopped and the bore-hole pressure was allowed to dissipate. Figure 5 shows a graph of the down-hole pressure data at inadvertent return Location 1.

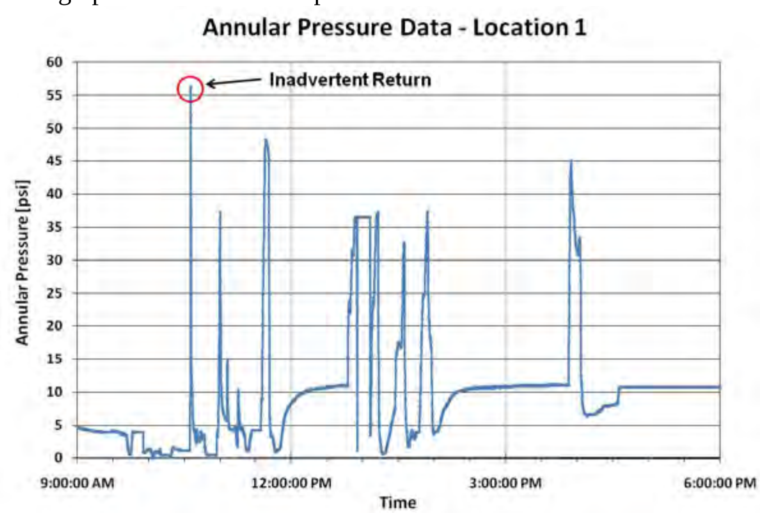
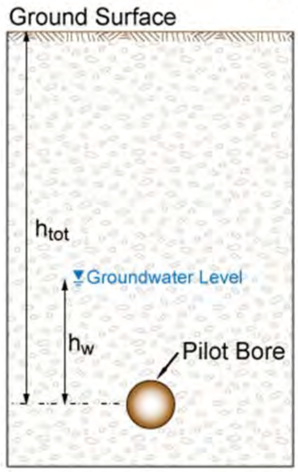


Figure 5. Annular Pressure Data at Location 1 during Inadvertent Return

B. Location 2

The second site for analysis was an HDD that was constructed in alluvial deposits comprised primarily of medium dense sands with some silt and gravel. At the location of the inadvertent return the bore was approximately 30 feet deep and had groundwater at the ground surface. The geotechnical investigation for the project included vertical borings with split spoon sampling. Figure 6 shows the bore geometry at the location of the inadvertent return as well as the soil parameters. Only the soil unit weight was provided in the soils report. The other soil parameters in Figure 6 were estimated based on published values.

Location 2



Parameters	Values
h_s	30 ft
h_w	30 ft
R_0	6 in
γ	130 pcf
ϕ	28°
c	0 psf
ν	0.30
E	125 tsf
G	96,000 psf

Figure 6. Location 2 - Geometry and Soil Parameters

At Location 2, the pilot bore was nearing the exit location when the inadvertent return occurred. Like Location 1, it is believed that the borehole collapsed just prior to the inadvertent return. As circulation was lost, the annular pressure increased, and drilling fluids were then observed at the surface. Figure 7 shows the down-hole pressure readings throughout the duration of the inadvertent return.

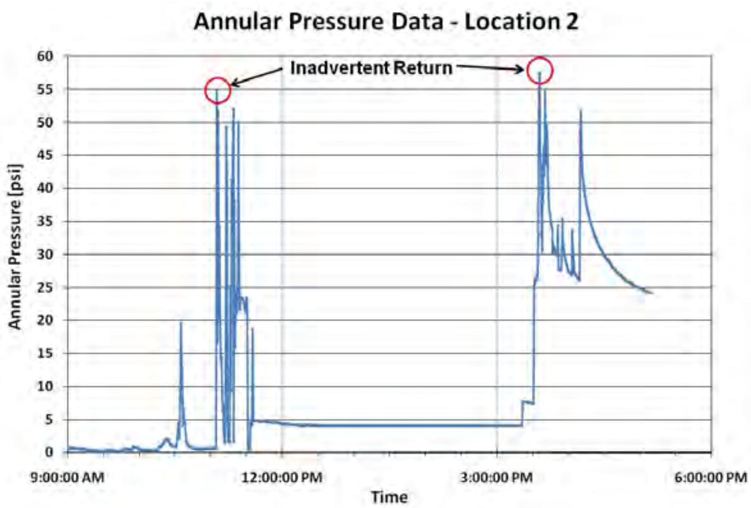


Figure 7. Annular Pressure Data at Location 2 during Inadvertent Return

After the initial inadvertent return occurred just prior to 12:00 pm, the drilling fluid escape path was allowed to "heal" and drilling continued once an open borehole was reestablished. However, an additional inadvertent return occurred after 3:00 pm at the same location when the bore once again collapsed.

5. COMPARISON OF DOWNHOLE PRESSURE MEASUREMENTS AND PREDICTED VALUES

For each of the inadvertent return locations, the measured down-hole pressure readings were compared to the predicted maximum pressure using the cavity expansion model with the radius of the plastic zone at the ground surface (Table 4).

Table 4. Predicted and Measured Limiting Pressures Using the Cavity Expansion Model.

	Location 1	Location 2
Maximum Pressure using Cavity Expansion Model with R_{pmax} at the ground surface.	314 psi	133 psi
Measured Pressure Causing Inadvertent Returns	56 psi	55 psi

Clearly setting R_{pmax} at the ground surface yields a calculated maximum pressure that was much higher than the actual pressure that caused inadvertent returns. When considering its influence in the maximum pressure equation and the localized nature of the plastic zone from the bore, it is not realistic to assume that R_{pmax} would reach the ground surface before hydrofracture occurs. Hongwei Xia conducted a series of large and small scale experiments at Queen's University and was able to show that the Delft equation grossly over-predicted the maximum pressure when using R_{pmax} at the ground surface (Xia, 2009), in some cases by more than 150%. He further recommended a factor of safety on the maximum mud pressure of at least 2.5.(Xia, 2009)

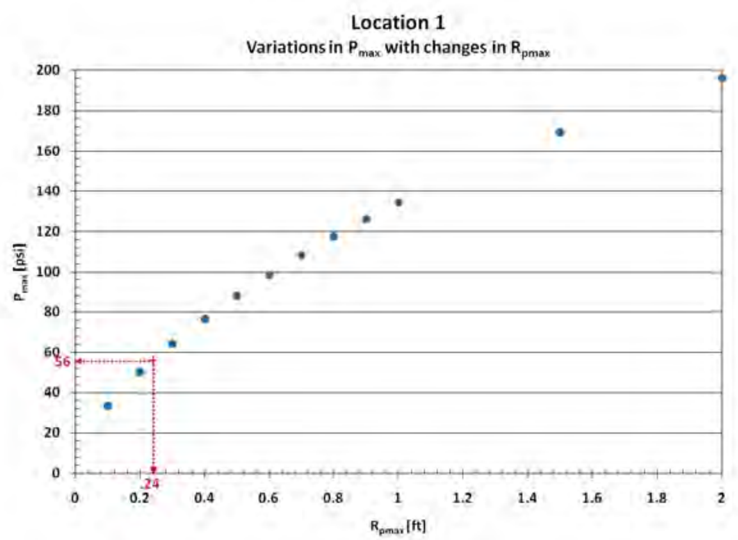


Figure 8. Location 1 Frac-out Pressure and Plastic Zone Radius

Figure 8 shows the radius of the plastic zone corresponding to the pressure at which inadvertent returns occurred at Location 1. The material was hard silt and had a very small expansion of the cavity of only ¼ ft prior to reaching the pressure in which inadvertent returns actually occurred.

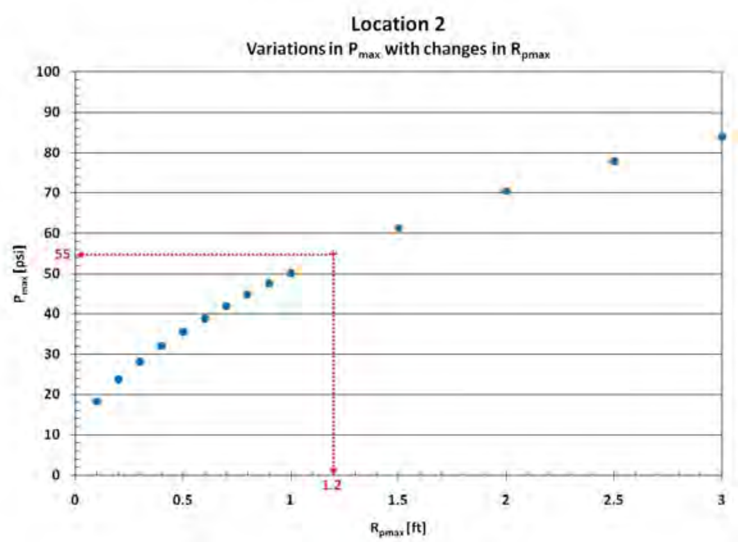


Figure 9. Location 2 Frac-out Pressure and Plastic Zone Radius

Figure 9 shows the radius of the plastic zone corresponding to the pressure at which inadvertent returns occurred at Location 2. The material for this bore was medium dense sand with some silt and gravel. According to the Delft equation, the radius of the plastic zone at the pressure where the inadvertent return occurred was approximately 1¼ ft.

6. CONCLUSIONS

After analysis of Figures 8 and 9, we conclude that the use of the maximum pressure calculation as shown in Equation 1 overestimates actual pressure at which inadvertent returns occur when using large values of R_{pmax}. The accuracy of the predicted maximum pressure could be improved by calculating P_{max} when R_{pmax} is very small (on the order of 2-3 bore-hole diameters or less). Alternatively, a safety factor should be applied to the calculated maximum pressure value with R_{pmax} calculated at the ground surface. Engineering judgment must be used to limit the hydrofracture pressure for a conservative design. Although the cavity expansion model is a valid method of calculating maximum pressures, it is clear that all input variables must be thoroughly understood before accurate predictions may be made. To this end, it is important that more down-hole pressure data be collected and compared with cavity expansion predictions where inadvertent returns occur so that we may gain a better understanding of the plastic zone behavior.

7. REFERENCES

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