Comparison of Inadvertent Return Risk Analysis Methods to As-Drilled Pressure Data and Review of the Concept of a Factor of Safety

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ABSTRACT
Most Horizontal Directional Drilling (HDD) projects in North America that include an engineered design, complete an annular pressure analysis prior to construction in order to mitigate risk of inadvertent returns (“frac out”). Although the accepted fluid models accurately predict actual drilling fluid pressure downhole, the accurate prediction of containing/confining pressure (i.e. hydraulic fracture or shear failure) continues to be a focus of research.

HDD contractors often continuously monitor annular pressure during construction to provide a basis for mitigating risk of inadvertent returns. The pressure sensor and associated guidance software automatically record “real-time” pressure data throughout the length of the HDD crossing. This “as drilled” annular pressure data, collected from a multitude of HDD crossings, is used in combination with CCI inspection reports to determine the date, time, and pressure magnitude of actual hydraulic fracture occurrences. Through careful evaluation, occurrences of inadvertent returns have been isolated within the as drilled data sets and plotted for comparison against predicted hydraulic fracture pressures calculated by both the “Delft” and “Queens” equation using site specific geotechnical parameters. Finally, performance of the models’ for predicting potential inadvertent return during construction are discussed

Real time annular pressure data has been collected for many HDD installations and the actual fracture pressures have been quantified. A comparison between the Delft, Queens and real time inadvertent return data is made in order to assess the performance of each method. In addition, the concept of a crossing factor of safety versus factored calculation is reviewed to provide insight in how to evaluate the safety of HDD methods for crossings.

1 INTRODUCTION

Hydrofracture 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, and the expected confining or “frac-out” pressure. These are two exclusive parts of the evaluation; however, the underlying principle is that the expected fluid pressure should maintain below the soil confining pressure, otherwise hydraulic fracture may occur.

The calculation methods that are available to estimate the soil confining pressure are plentiful, however the effectiveness of each method is still debated. The methods that are widely used for the soil confining pressure calculation are the “Delft Equation” (Luger and Hergarden, 1988), “Queens Equation” (Lan and Moore, 2016 or Xia, 2009), and the so called “Total Stress Equation”. Each the Delft equation and Queens equation, have different appearances depending on drained or undrained assumptions.

It is very important to understand the differences between these methods, however this research will not be going through the assumptions and differences between the calculations, but rather, how the final results of each equation compare with actual frac-out data obtained during HDD construction.

2 METHODOLOGY

2.1 Data Analysis

The method for finding the inadvertent return events has been developed in more detail previous works (Boelhouwer et al., 2019).

To complete this analysis, the as-drilled annular pressure data, in combination with HDD construction inspection reports, have been 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.

In order to find the pressure magnitude of each hydraulic fracture occurrence the general timeframe must be established. Construction reports pertaining to the specific crossing are carefully reviewed and indications of any hydraulic fracture events are noted. Once the general timeframe and location along the drill path are confirmed, the pressure data can be narrowed to these boundaries.

While reviewing the pressure information it is very important to note that discontinuities in the data exist.

"Shorts" in the data occur when some type of interference in the data is present, such as loose electrical connection or moisture. These "shorts" can be identified because they have an extreme increase or decrease of false pressure in a very short timeframe.

To identify a hydraulic fracture within the data, the largest real pressure before the release is observed on surface, has ben taken as the fracture pressure. Often the data will show a distinct trend as shown on the chart in Figure 1

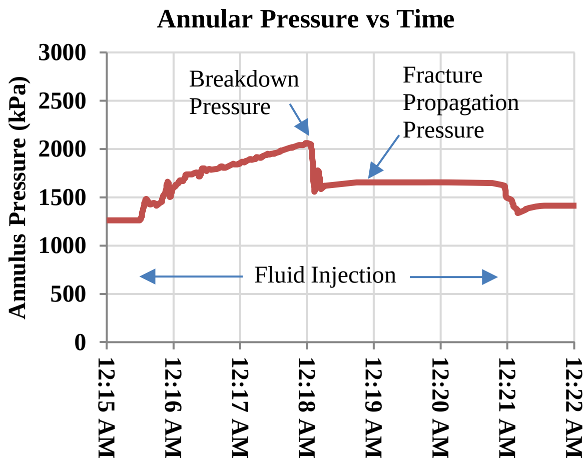

Figure 1: Hydraulic fracture characteristic curve. During the injection phase, drilling fluid is introduced into the borehole through the drill bit.

During analysis, most times subtle sloped pressurizations can occur. The pressurization stage leading to fracture can be quite slow; however, breakout is evident due to a sharp drop in pressure post peak.

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

Review of actual hydraulic pressure data distributions during construction has been completed for nearly 60 HDD projects. Ultimately, not all of those cases contain inadvertent return events (thankfully), therefore 13 inadvertent return events have occurred within clayey soils and are assessed in this research.

The intention of this research is to compare the effectiveness of the various methods used to calculate the confining pressure of the geotechnical materials surrounding the borehole wall. The methods used will not be described in detail, however, assumptions made in the models will be outlined.

2.2 Comparison of Methods

The analysis completed and used to compare calculation methods included completion of an assessment of how each calculated hydraulic fracture data point compares to an actual hydraulic fracture data point. A calculated data point is that pressure value which is calculated by one of the methods. An actual data point is the pressure at which an inadvertent return occurred within the construction data. In addition, there is a "perfect prediction" line, where the calculated pressure values match the actual pressure values. If the trend line of a particular data set resides below the perfect prediction line, we can say that is a conservative equation and if the data line of best fit resides above the perfect prediction line, we can say it is unconservative.

Valid calculation methods in clayey soils may be in drained or undrained conditions. Typically, undrained conditions are used for short term "during construction" timeframes. The term undrained refers to a soil type that does not allow pore pressure dissipation in the short term, or soils with low permeability, and no volume change within the soil mass occurs. The assumption of a drained condition is utilized when pore pressure may dissipate in the short term and volume change of the soil mass occurs.

First, in order to show the methodology described above is a suitable way to assess each equation, the Total Stress method is modelled below. We know that the Total Stress method is a conservative assessment for estimating the confining pressure because it does not consider strength within the soil mass surrounding the borehole.

$$P_{max} = (\gamma_B)(H) \quad [1]$$

γ_B – Bulk Unit Weight
H – Height to Surface

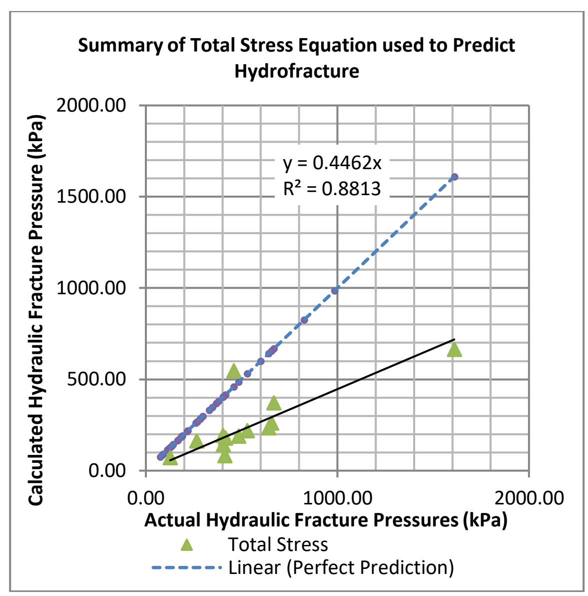

Figure 2. Summary of Calculated and Actual Fracture Pressures using Total Stress Equation

As shown in Figure 2, the calculated values of the actual hydraulic fracture pressures in clay are lower than the actual fracture pressures in all but one case. The equation of the trendline shows that this method should underpredict the actual pressure at a rate of 0.4462 times and the “spread” of the data is considered good with an R^2 value of 0.8813.

The second method used to estimate the confining pressure is the Delft equation using undrained parameters (phi=0).

$$P_{max} = [\sigma_0 + S_u] \quad [2]$$

σ_0 – Total Stress
S_u – Undrained Shear Strength

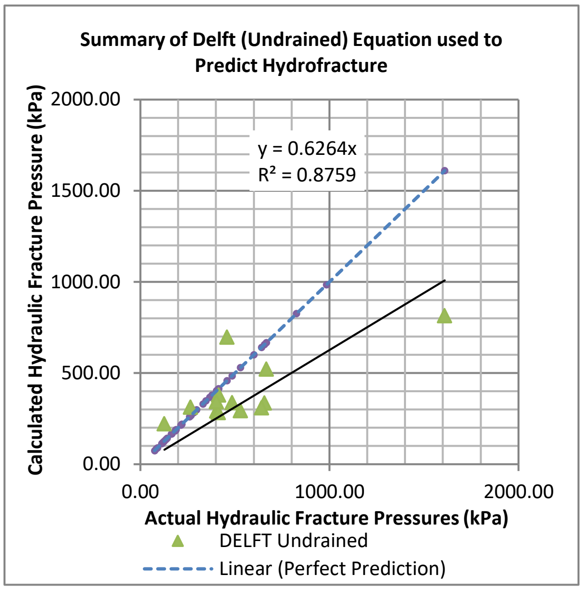

Figure 3. Summary of Calculated and Actual Fracture Pressures using Delft (Undrained) Equation

As shown in Figure 3, the data generally plots beneath the perfect prediction line which suggests the method on average is conservative. The equation of the line of best fit shows the data predicts the actual fracture pressure at a magnitude of 0.6264 times the actual pressures and the fit of the data is good with an R^2 value of 0.8759.

The next equation used to predict hydraulic fracture is the Queens equation (Xia, 2009, Lan and Moore, 2016). The Queens equation contains a maximum plastic radius, and therefore the comparison was completed in two forms. The first was the general form of the equation using an Rp_{max} value similar to what has been previously assumed by many for the Delft equation; one half the height to surface. The second form of the Queens equation assumed a more localized Rp_{max} value; within approximately three pilot hole diameters ($3D_0$) distance from the borehole wall.

$$P_{max} = S_u + 0.5(3\sigma_h - \sigma_v) - S_u \ln\left[\left(\frac{R_0}{R_p}\right)^2 + S_u/G\right], for\ k'_0 < 1 \quad [3]$$

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σ_v – Total Stress (Vertical Stress)
σ_H – Horizontal Stress
S_u – Undrained Shear Strength
R_p – Plastic Radius
R_0 – Borehole Radius
G – Shear Modulus
k'_0 – Horizontal Earth Pressure Coefficient (at rest)

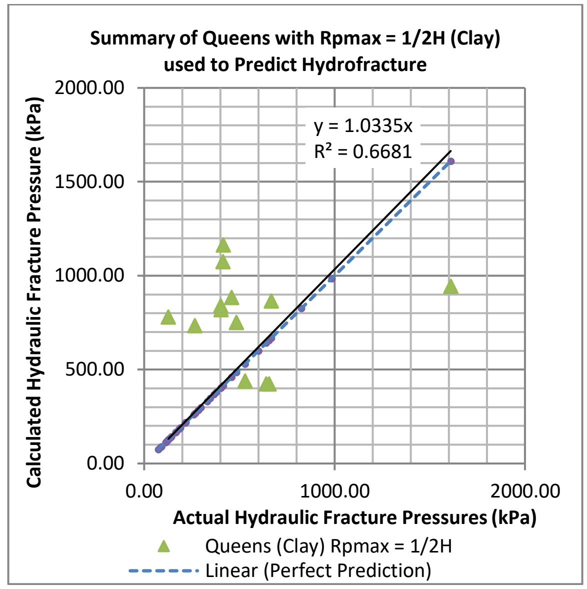

Figure 4. Summary of Calculated and Actual Fracture Pressures using Queens Equation (Rpmax=1/2H)

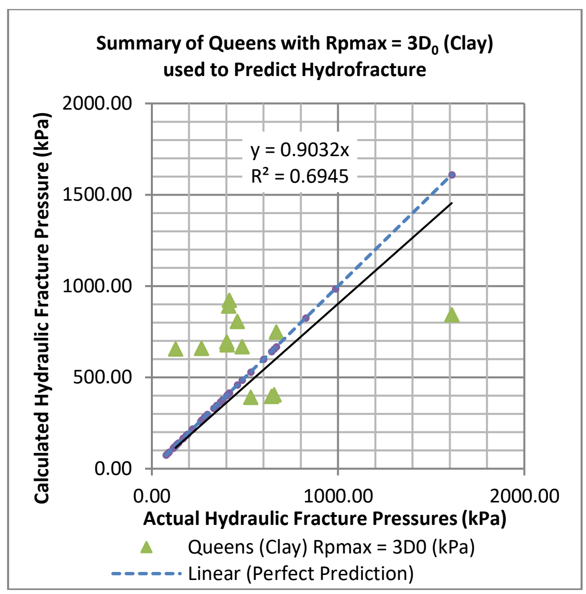

Figure 5. Summary of Calculated and Actual Fracture Pressures using Queens Equation ($Rpmax=3D_o$)

As shown in both Figures 4 and 5, the equation is a good estimate of the actual IR pressures and trendlines fall close to the perfect prediction line, however the data fit is less attractive according to the R^2 values (0.6681 to 0.6945). In lieu of the above data comparison, it appears that the maximum plastic radius does not have a significant effect on the final result. Therefore, a sensitivity analysis was completed for the Queens equation in order to better assess which parameters have the largest effect on the confining pressure. Figure 6 shows a “Spider Diagram” which helps show how changing a parameter from the average modifies result of an equation. The diagram was completed using average values of typical soil parameters shown in Table 1.

Table 1: Average Soil Properties Used for Sensitivity Analysis

Soil Parameter	Average Value [ ]
Unit Weight (γ)	17 kN/m^3
Pilot Hole Radius (R_o)	0.15 m
Height to Surface (H)	20 m
Maximum Plastic Radius (Rp_{max})	10 m
Coefficient of Lateral Earth Pressure (K)	1
Shear Modulus (G)	8000 kPa
Undrained Shear Strength (Su)	100 kPa

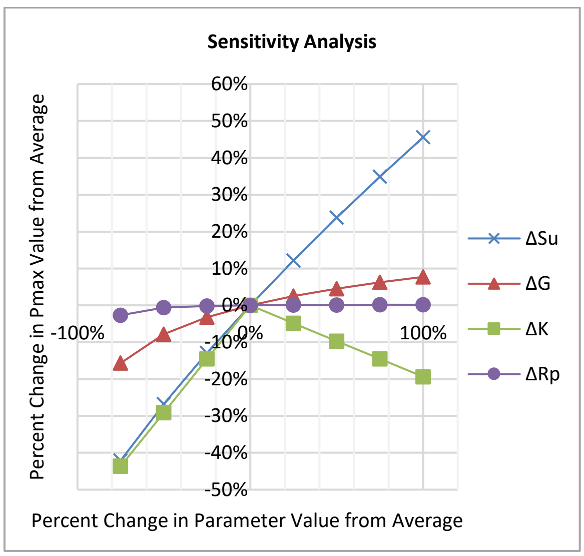

Figure 6. “Spider Diagram” showing the sensitivity analysis completed for the Queens Equation

The chart in Figure 6, shows that the horizontal earth pressure coefficient and undrained shear strength values have the largest effect on the output. Undrained shear strength is a soil property that may be estimated with some degree of accuracy using correlations to literature or it can be directly measured in the laboratory. Engineering judgement is required when assigning an undrained shear strength to the soil. Unfortunately, the lateral earth pressure coefficient is not as easily assigned or measured in practice. Normally consolidated or over consolidated clays can exhibit very different lateral earth pressure behavior. Interestingly, the maximum plastic radius does not have a significant effect on the calculated confining pressure and doubling the shear modulus only increases the confining pressure by nearly 10%. Decreasing the shear modulus provides a larger impact in reducing the total confining pressure.

The fourth and final equation used for this assessment is the drained version of the Delft equation. Generally, for short term conditions such as HDD construction, an undrained assessment should be used. However, if one can make the argument that the clay is stiff, and over consolidated, such as the soils encountered in areas affected by glacial retreat, then there may be fissures and micro-fractures within the clay that can allow pore pressure dissipation in the short term. Therefore, these equations should be used with caution, however, can have a place in design.

Similar to the previous analysis with the Queens equation, the data was analyzed in two ways; the first using the assumption that Rp_{max} extends half the distance to surface, and the second using a localized Rp_{max}. The method of using a more localized Rp_{max} value is a valid way to increase the accuracy of the Delft equation when compared with actual fracture pressures, as shown by Boelhouwer et al. (2019). The Delft equation is shown below (Luger and Hergarden, 1988).

$$P'_{max} = [\sigma'_0(1+\sin\varphi) + c\cos\varphi + c\cot\varphi]\left[\left(\frac{R_0}{R_{p,max}}\right)^2 + \frac{(\sigma'_0 \cdot \sin\varphi + c \cdot \cos\varphi)}{G}\right]^{\frac{-\sin\varphi}{(1+\sin\varphi)}} - c\cot\varphi \quad [5]$$

σ'_0 – Effective Stress
φ – Friction Angle
c – Cohesion
$R_{p,max}$ – Maximum Plastic Radius
R_0 – Borehole Radius
G – Shear Modulus

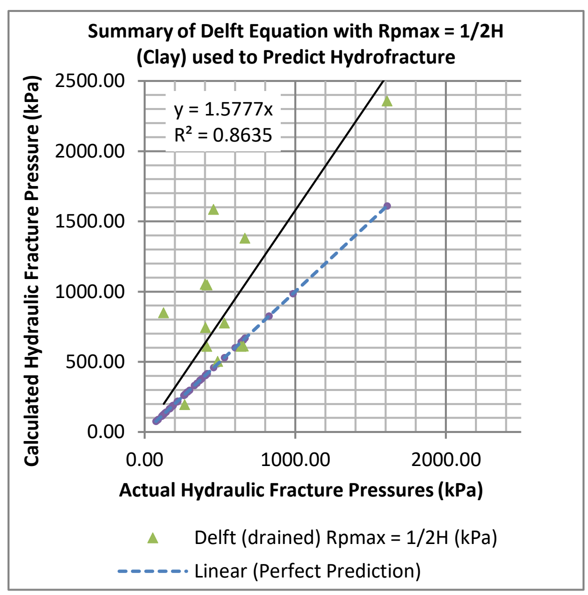

Figure 7. Summary of Calculated and Actual Fracture Pressures using Delft Equation (Rpmax=1/2H)

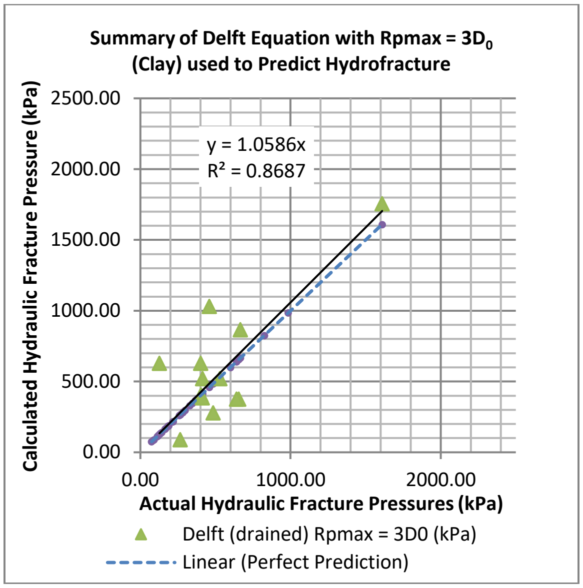

Figure 8. Summary of Calculated and Actual Fracture Pressures using Queens Equation (Rpmax=3D₀)

Figures 7 and 8, show the drained Delft equation with a varied Rp_{max} value. The graphs show that the Delft equation is sensitive to the value of Rp_{max} selection, and when the larger value is chosen the method is unconservative with an average over prediction of 1.577 times the actual fracture pressure, however the data fit is considered good with an R^2 of 0.8635. By using a smaller, more localized Rp_{max} value the data becomes slightly overconservative, overpredicting the actual fracture pressures by a factor of 1.0586 times, while maintaining a good fit of the data with an R^2 value of 0.8687.

3 SUMMARY

3.1 Results

The results of the analysis are summarized in Table 2. It should be noted that a factor within 10% of the perfect prediction line are considered a “good” estimate and anything outside this band are listed as an over prediction or under prediction.

Table 2: Summary of Results

Method	Over Under Good	Factor	Data Fit (R^2)
Total Stress	Under	0.4462	0.8813
Undrained (Delft)	Under	0.6264	0.8759
Queens (Rp_{max}=1/2H)	Good	1.0335	0.6681
Queens (Rp_{max}=3D_0)	Good	0.9032	0.6945
Delft (Rp_{max}=1/2H)	Over	1.5777	0.8635
Delft (Rp_{max}=3D_0)	Good	1.0586	0.8687

The results show that the value of maximum plastic radius does not have a significant influence on the result of the Queens equation. Although the Queens equation had the lowest R^2 value, it was a good predictor of soil confining pressure on average no matter the size of the plastic radius. By limiting the maximum plastic radius to 3 pilot hole diameters, the delft equation becomes the best combined result when considering the data fit as well as pressure prediction, however when the plastic radius grows, this method quickly becomes unconservative. Finally, the Total Stress and Delft (Undrained) methods are considered ultra conservative and should only be used in preliminary design, or when permissible conditions are present (i.e., blowout).

3.2 Concept of Factor Of Safety (FoS)

The concept of the factor of safety for an HDD crossing has been a topic of discussion over the past few years. The idea of factor of safety of the crossing when reviewing the inadvertent return or “frac-out” risk requires more definition. A FoS for the crossing should be analogous to the global FoS in geotechnical engineering – applied stress divided by allowable stress. This would lead to a FoS for the crossing when assessing risk of inadvertent returns equating to drilling fluid pressure (applied stress) divided by the confining pressure (allowable stress). The challenge in utilizing this method for HDD prior to the research herein was that it was unknown how effective the previously noted methods were at predicting the actual fracture pressures. Without knowing how well the allowable stress predicts failure, there could be substantial error in the factor of safety calculation. The research shows now that each method has an amount of effectiveness and the factor of safety required for a particular crossing may be higher or lower, depending on the method used to calculate confining pressure.

RECCOMENDATIONS

It is recommended that:

- Further research comparing actual pressure data to these methods is completed, and additional correlations developed to further understand the differences
- Completion of Finite element modelling and comparison to analytical and construction data to further understand the differences of these methods
- Additional, more controlled large-scale experiments to simulate inadvertent return to be completed. A more controlled experiment would allow certain parameters to be manipulated and could assist in further understanding of this mechanism.

4 CONCLUSION

The analysis completed has compared the most common ways to calculate the confining pressure of soil surrounding HDD boreholes to actual pressure information obtained during construction. The comparison between the actual fracture pressures and the calculated fracture pressures indicated that there are merits and pitfalls of using each method.

Hydrofracture evaluation can be completed using various methods, however, as indicated from this research, some are overly conservative, and some can be under conservative. The total stress and Delft equation using undrained conditions are overly conservative. The limited number of parameters and simplistic additive components in each of these methods do not allow for a large amount variation in the confining pressure value and therefore both can be considered conservative approaches for a range of permissible soil parameters.

According to this research, the drained version of the Delft Equation and the Queens Equation can be better predictors of the actual confining pressure however, the complexity of these equations must be understood as the parameters used have significant influences on the result. Utilizing a more localized R_{pmax} value in the Delft equation (drained analysis) appears to predict the actual fracture pressures more accurately and precisely and an extended maximum plastic radius tends to be unconservative. The Queens equation appears to predict the confining pressures well, however there is a degree of data scatter from this review. Interestingly, the maximum plastic radius does not have as significant of an effect on the result, which, due to the challenges designers have in selecting an appropriate value for this parameter, is likely a benefit. The Queens equation does incorporate the effect of the soil lateral earth pressure which is important in determining maximum and minimum stress around a circular opening (such as a borehole), however this parameter can be difficult to estimate in practice.

The findings from this research generally agree and complement a number of other written literature on the subject of hydrofracture evaluation. It is a subject that has been researched extensively, yet there is still uncertainty in the trenchless community on the differences methods that may be used. The accuracy and factors used in each equation should be independently evaluated by the designer to ensure safety against inadvertent return.

5 REFERENCES

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