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Impact of Shear Modulus on Maximum Allowable Pressures in HDD

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Abstract. This paper focuses on the effect of shear modulus on maximum allowable pressures of drilling fluid applied to maintain the stability of a borehole in Horizontal Directional Drilling (HDD). HDD is one of the widely used trenchless methods to install and replace underground pipelines and utility conduits. Despite the popularity and success, borehole instability caused by tensile is still considered as a major challenge in drilling. While there are analytical and numerical models used to design the maximum allowable drilling fluid pressures based on soil profile, the uncertainty in selection of the representative values of soil properties including shear modulus can have an impact on the predicted drilling fluid pressure. Data from field experiments on drilling fluid pressures was used to validate the existing analytical models and the effect of shear modulus is presented. Results indicates that maximum pressures of drilling fluid increase with increasing shear modulus, however this increase depends on the assumption of the radius of plastic zone, which is closely related with the borehole diameter. The results from this study can significantly help in reducing the risks associated with borehole instability, thus lowering the drilling time and cost.

Keywords. Maximum allowable pressure, hydraulic fracture, borehole stability, large strain shear modulus.

1. Introduction

Due to high social and environmental impact of open cut trenching, horizontal directional drilling (HDD) has become very popular for underground utility and pipeline installations. Developed in the early 1970s, HDD is an effective method for underground construction, especially in difficult circumstances where minimal surface disruption is required, such as busy intersections and congested roads, or where obstacles need to be bypassed, such as river crossings, highways, mountains, and lakes [1, 2, 3]. HDD consists of three main steps in the construction process: 1) drilling of the pilot hole, 2) reaming of the pilot hole, and 3) pulling back of pipe string. A schematic of an HDD is given in Figure 1.

A drilling fluid that consists of bentonite and/or polymer with water is used during drilling of the pilot borehole. The fluid is circulated through the borehole used for many purposes including maintaining the minimum borehole pressure within the borehole to prevent collapse and provide stability. While the drilling fluid should be maintained at the minimum, it shouldn't exceed a certain pressure that a soil layer can withhold. The fluid pressures greater than maximum allowable pressures result in inadvertent returns

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and loss of drilling fluid that create economic and environmental problems. Therefore, a correct estimation of minimum required, and maximum allowable fluid pressures is needed.

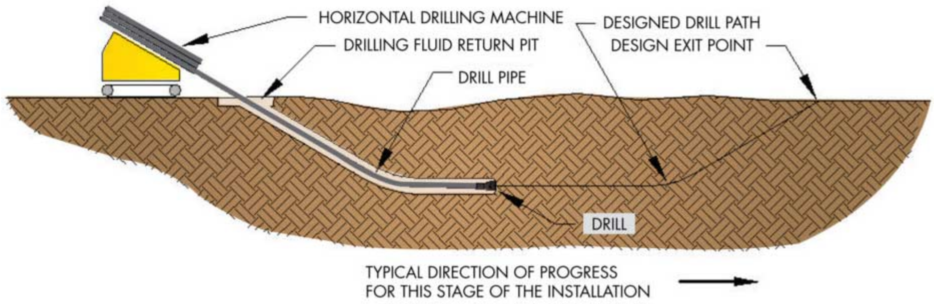

Figure 1. Drilling of a pilot borehole in HDD.

Unlike maximum allowable pressure, estimation of minimum drilling fluid pressures is straight forward, and it has been very well established (API 2017). Maximum allowable pressures on the other hand is often difficult to predict as it is directly related with the failure mechanisms of soils. There are two main failure mechanisms that can occur during an HDD: shear and tensile. The first mechanism is associated with generalized shear failure which generates unconfined plastic flow in surrounding soil, so called "blowout", e.g. [4]. The latter causes fracture initiation and consequent propagation as known as hydraulic fracture. Theoretical and experimental studies have been performed to better understand the failure mechanisms when pressures exceed soil strength to ultimately develop reliable models to estimate maximum allowable drilling fluid pressures. While the most commonly used and adopted approach is the Delft equation [5], improvements have been made to develop Maximum Strain method by [6]. Both models use shear modulus as a parameter to calculate maximum allowable fluid pressures in HDD.

This study focuses on the effect of soil shear modulus on maximum allowable borehole pressures in HDD. This information is relevant because the shear modulus can significantly affect the allowable drilling fluid pressures during horizontal drilling. Accurate determination of shear modulus is difficult and not well understood in practice [7]. Further, shear modulus (G) is rarely provided in a standard geotechnical report, making an appropriate selection difficult. The common approach to determine shear modulus is to calculate the shear modulus from average values of elastic modulus and Poisson's ratio from soil classifications that is in fact maximum strain shear modulus (G_{max}). However, soil experiences much higher strains because of the applied mechanical forces. Therefore, using G_{max} as an input value to calculate allowable pressures does not represent actual field conditions. Therefore, a better understanding of the effect of shear modulus is needed. To tackle this issue, first field data from soil failure during HDD are collected. Then a parametric analysis was performed using two closed-form analytical equations to quantify maximum allowable pressure and the results are compared with field data.

2. Background

Maximum allowable drilling fluid pressure is defined as the maximum pressure that soil can sustain without failure during horizontal directional drilling. As the borehole is drilled and material is removed, a stress relief must be overcome to attain equilibrium. The drilling fluid introduces a radial pressure against the borehole wall which acts as a support to the bore-wall and relieves the generated tangential stress. When the hydraulic pressure in the borehole exceeds the strength of the surrounding strata, hydraulic fracture occurs where drilling fluid escapes from the borehole and can migrate to the surface [8]. [9] reported that the mechanisms of fracture in low-permeability soils appeared to be of a tensile failure mechanism. This was enhanced by the generation of pore pressure as the soil around the borehole was sheared due to the radial–tangential stress difference imposed by the injected pressure. [10] also confirmed that the maximum allowable fluid pressure to prevent mud loss by hydraulic fracture is the pressure that initiates tensile stresses in the soil.

The cavity expansion model has been used in evaluating hydraulic fracture risks, specifically maximum allowable drilling fluid pressures, for the majority of HDD projects in soils. Two major models that use cavity expansion theory are proposed: Delft and Maximum Strain equations. Assumptions to formulate the Delft equation are: (a) borehole is axisymmetric and soil is isotropic, homogeneous and have infinite size; (b) stress response is elastic until onset failure as defined by the Mohr-Coulomb failure criterion; and (c) elastic deformation is governed by Hooke's law. The maximum allowable pressure is measured at the largest radial displacement, or when plastic expansion occurs (e.g. [7]) as shown in Figure 2. The maximum allowable pressure in the Delft equation can be calculated as follows:

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

where p_{max} is maximum allowable pressure (Pa), u is groundwater pressure (Pa), φ is soil friction angle (°), c is cohesion of soil (Pa), R_0 is borehole radius (m), $R_{p,max}$ is radius of the plastic zone (m), G is shear modulus (Pa), and σ'_0 is initial effective stress (Pa).

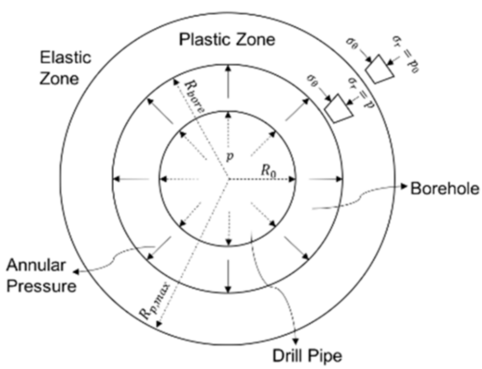

Figure 2. Elasto-plastic cavity expansion.

Maximum strain method developed by [10] utilizes the cavity expansion theory. Compared to the Delft equation, this method uses maximum hoop strain around the borehole instead of the Mohr-Coulomb failure criterion and Hooke's Law. If the strain around the borehole exceeds its upper limits, drilling fluid is pushed aside and cracks form. Assuming a maximum allowable strain (2% and 5% strains) for a borehole, maximum allowable pressure can be calculated as follows [6]:

$$P_{\max} = \left\{ \left[\varepsilon_{\theta,\max} \times \frac{2G}{P_0 + c \cdot \cot\varphi} \times \frac{1+m}{1-m} \right]^{\frac{1-m}{1+k}} \times \frac{2}{1+m} \left(P_0 + c \cdot \cot\varphi \right) \right\} - c \cdot \cot\varphi \qquad (2)$$

where $\varepsilon_{\theta,max}$ is the maximum allowable strain, P_0 is initial stress of soil (Pa), ψ is the dilation angle of the soil (°), m=(1-sinφ/1+sinφ), and k=(1-sinψ/1+sinψ).

Fluid pressures exceeding maximum allowable limits can cause fluid loss and large displacements that are significant issues to avoid in HDD projects. A successful horizontal directional drilling without any fluid loss or blow-out doesn't only depend on drilling fluid pressure inside of the borehole, but also stress state and strength parameters of the surrounding soil. The stability of a horizontal borehole and drilling fluid pressures are determined by several influencing factors such as depth of cover, borehole diameter, cohesion, friction angle, shear modulus, and unit weight of soil.

3. Test data and discussion

To investigate the effect of shear modulus, data sets from field tests are collected from the literature. The data includes site description, borehole diameter, soil properties, and borehole fluid pressures at failure. The details of properties of soils are given in Table 1.

Table 1. Properties of soils.

Reference	Cohesion (kPa)	Friction angle (°)	Elastic Modulus (kPa)	Poisson ratio	G_{max} (kPa)
Staheli	0	30	11970	0.33	4596
Keulen Strd	0	30	25000	0.33	9375
Keulen BTL47(1-2)	0	30	10000	0.33	3759
Keulen BTL47(3)	5	25	5000	0.37	1825
Keulen BTL48	0	40	15000	0.26	5952

Keulen [6] performed a series of field tests in sand to investigate maximum allowable fluid pressures that initiate hydraulic fracture. The data from four tests denoted as BTL47(1-2), BTL47(3), BTL48, and Standard case were used. During experiments, the drill bit was pushed to the depth of 9.6 m in BTL47-12, 3.35 m in BTL47-3, 0.30 m in BTL48, and 6.67 m for standard case and drilling fluid pressures at failure were measured. In the field experiments of [11] alluvial deposits comprised of medium dense sand with silt and gravel were drilled along the pilot borehole path. It is reported that the inadvertent return of drilling fluid was observed when the pilot borehole was near the exit location. 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. The details of field HDD experiments are given in Table 2.

Then the data sets used as input parameters in Delft and Maximum Strain equations to calculate maximum allowable pressures for comparison with actual pressures within boreholes at failure.

Table 2. HDD experiment details.

Reference	Borehole diameter (m)	Cover depth (m)	Effective stress (kPa)	Pressure at failure (kPa)
Staheli	0.15	9.14	97	386
Keulen Strd	0.20	6.67	102	-
Keulen BTL47(1-2)	0.08	9.60	63	210
Keulen BTL47(3)	0.08	3.35	42	65
Keulen BTL48	0.03	0.30	160	370

As a first step in the analysis, maximum allowable pressures are estimated to quantify the effect of input variables using Delft and Maximum Strain equations. Maximum pressures increased with increasing unit weight of the soil as expected but the slope of the curves from both equations are different as shown in Figure 3(a) and 3(b). Staheli and Keulen Strd cases are used as they are the only experiments provided with the unit weight of the soil and the values range between 16-22 kN/m^3 in the analyses. The effect of effective stress from both Delft and Maximum strain models are given in Figure 3(c) and 3(d). This information is relevant if an HDD is being constructed in urban areas where additional forces are transferred to soil profiles. In the analysis, the minimum effective stress that soil is subjected in the field and increased values of effective stress were used. The maximum pressures increased at a same rate both in Delft and Maximum strain models with increasing effective stress.

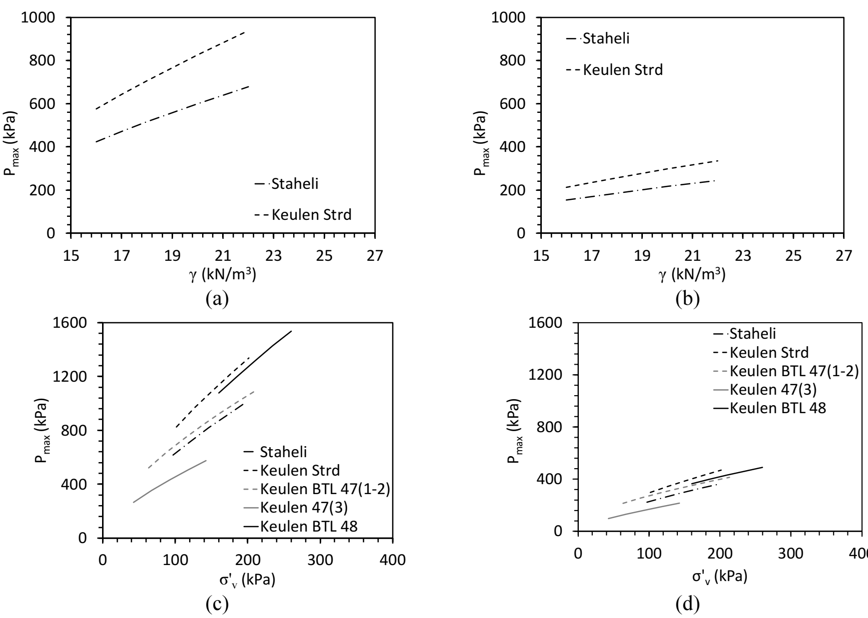

Figure 3. Maximum allowable pressures (a) effect of unit weight on maximum allowable pressure in Delft; (b) effect of unit weight in Maximum strain; (c) effect of effective stress in Delft; (d) maximum pressures with effective stress in Maximum strain.

The selection of radius of plastic zone ($R_{p,max}$) during HDD to estimate the maximum allowable fluid pressures is one of the most controversial issues in Delft model. For purely cohesive soil, the radius of the plastic zone is recommended as half of the depth of the borehole from the crown to the ground surface ($R_{p,max}$=0.5h) while this value is two-thirds of the cover of depth ($R_{p,max}$=2h/3) for non-cohesive soils [12, 13]. However, in practice often P_{max} is calculated and multiplied by these empirical values, which result in inaccurate estimation of P_{max}. The maximum pressures normalized by effective stress at the crown of the boreholes are calculated for $R_0/R_{p,max}$ ratios between 0.05 to 1.00 and the results are given in Figure 4. The results indicate that the ratios greater than 0.5 do not influence maximum pressures while there is a significant effect of $R_0/R_{p,max}$ ratio smaller than 0.2.

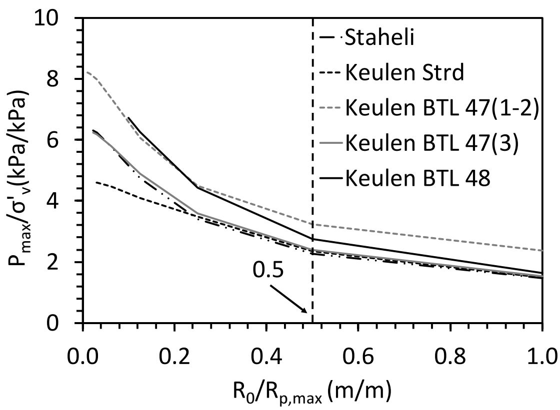

Figure 4. Effect of unit weight on maximum allowable pressure (a) Delft; (b) Maximum strain.

Finally, the impact of shear modulus is investigated to quantify the effect on the maximum pressures. The maximum pressures using different values of shear modulus are used in Delft and Maximum strain models and plotted in Figures 5(a) and 5(b). Although not can be seen its significance in the equations, the shear modulus had a significant effect on the pressures. For instance, maximum allowable pressures of 521 and 214 kPa were calculated when a G_{max} of 3759 kPa (Keulen BTL471-2) was used in the Delft and maximum strain equations, respectively. For the field soil from the experiment of Staheli having a shear modulus of 4596 kPa, the maximum pressures were calculated as 617 kPa from the Delft equation, while this value decreased to 434 kPa when the shear modulus was reduced to 1500 kPa. The maximum pressures increased by 25% when the shear modulus of all soils given in Table 1 is doubled and decreased by 29% with when shear modulus is decreased to a lowest value of 1500 kPa when Delft equation is used in [11] experiment as shown in Figure 5(a). Similar to the changes in maximum drilling fluid pressures in Delft equation, a 26% increase and 30% decrease in P_{max} were calculated from Maximum strain method. The lower values of shear modulus of soils used in the analyses correspond with the G/G_{max} range between 1.0-0.2 to account for the reduction in shear modulus. These results urge the use of representative values of shear modulus in the analyses.

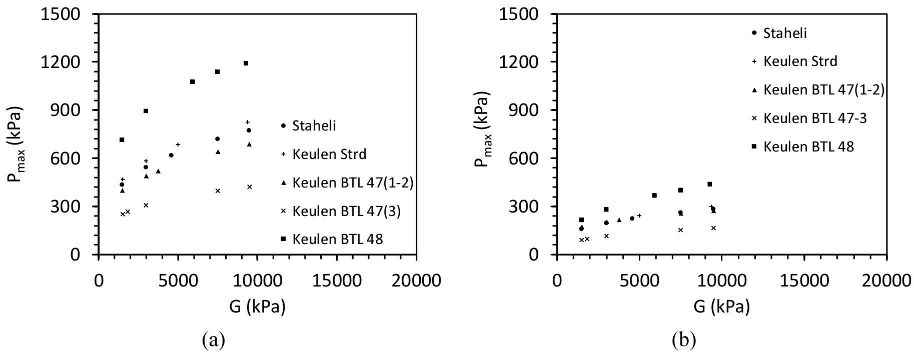

Figure 5. Relationship between shear modulus and maximum allowable pressure (a) Delft; (b) Maximum strain.

Further, it is worth to note that the input value of shear modulus in the analyses is the shear modulus at small strains. However, the Maximum strain model calculates maximum pressures at high strains as high as 2% recommended by [6] and yet incorporates G_{max} as an input parameter. It is well established that shear modulus of a given soil decreases with increasing strain under monotonic loading [14]. If a reduced value of shear modulus at large strains is used to calculate maximum pressures, more accurate results can be obtained. In addition, a further validation is needed.

4. Conclusions

This study focuses on the evaluation of two available methods, Delft and Maximum strain models developed based on cavity expansion theory, are used to investigate the effect of soil properties and horizontal directional drilling (HDD) design parameters on the maximum allowable drilling fluid pressures during HDD. A specific attention was given to understand the impact of shear modulus on the maximum allowable pressures and highlight the importance of using representative values of shear modulus of soils. A parametric study is performed using field HDD experiments as a basis and the results from models are discussed. The specific conclusions drawn from this study as follows:

- Maximum allowable fluid pressures increased by 58% when unit weight is increased from 16 to 22 kN/m3.
- Increase in effective stress influenced the maximum pressures by a minimum value of 17% and a maximum value of 70%. The maximum value was observed when the effective stresses were doubled.
- The maximum pressure increased by 25% when the shear modulus of all soils is doubled and decreased by 30% with when shear modulus is decreased to a lowest value of 1500 kPa using the Delft and maximum strain equations.
- The effect of shear modulus on maximum allowable fluid pressures was significant. A correct determination of shear modulus requires either laboratory of field experiments that lacks in actual HDD projects. Therefore, the use of an actual values of shear modulus is recommended.

The results and conclusions presented in this study are specific to data sets collected from field experiments. A more detailed yet robust method to estimate maximum allowable pressures that considers large strain conditions is being developed.

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