LIMITING DRILLING SLURRY PRESSURES TO CONTROL HYDRAULIC FRACTURING DURING HDD THROUGH PURELY COHESIVE SOIL

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ABSTRACT
Hydraulic fracturing is a problem associated with Horizontal Directional Drilling that is still inadequately understood and can result in serious consequences. During insertion of utility conduits and other buried pipe infrastructure, drilling slurry is used to stabilize the soil around the excavation zone prior to pulling the new pipeline into place. Hydraulic fracturing occurs when the drilling slurry flows through tensile fractures in the soil surrounding the excavated zone caused by the pressures of the slurry itself. Fracture creation depends on both the drilling slurry pressure inside the newly created conduit as well as the properties and stress state of the surrounding soil. Finite element analyses were performed to model the elasto-plastic response of undrained clays with varying soil properties. Both the trends associated with varying the material properties of the host soil and the phenomena governing fracture formation are discussed. Design formulae are presented to reflect soil parameters, slurry parameters, and the tensile strength of the soil. Results of calculations using another published design equation were examined and compared with those from the suggested design formulae.

RÉSUMÉ
La rupture hydraulique est un problème lié aux forages directionnels horizontaux qui est encore peu compris et qui peut avoir des conséquences graves. Pendant l'insertion des conduits de service et d'autres systèmes de tuyaux enfouis, la boue de forage est employée pour stabiliser le sol autour de la zone d'excavation avant de mettre en place la nouvelle canalisation. La rupture hydraulique se produit quand les pressions exercées par la boue provoquent des ruptures de tensions autour du site de forage, dans lesquelles la boue s'introduit. La création de rupture dépend de la pression à l'intérieur du conduit nouvellement créé aussi bien que des propriétés et des contraintes exercées sur le sol environnant. Des analyses d'éléments finis ont été exécutées pour modeler la réponse élastoplastique des argiles non vidangées avec les propriétés variables du sol. Les tendances associées aux variations des propriétés matérielles du sol et des phénomènes régissant la formation de ruptures sont discutés. Des formules de conception sont présentées pour refléter les paramètres du sol, les paramètres de boue, et la résistance à la traction du sol. Les résultats des calculs employant une autre équation publiée de conception ont été examinés et comparés à ceux des formules de conception suggérées.

1. INTRODUCTION

The advent of significant cost savings has increased the acceptance and use of trenchless construction techniques over the past 25 years. Traditional cut-and-cover methods are often replaced in favour of these newer construction techniques that are consistently less disruptive and more cost effective (Allouche et al. 2000). Horizontal Directional Drilling (HDD), one of these trenchless installation methods, allows buried conduits to be installed at a lower financial and environmental cost than traditional methods. HDD also allows installation of these conduits, such as sewer or waste water pipes, in areas that would not be suitable for a cut-an-cover installation – beneath a highway or river for example. However, the HDD process is still not yet full understood. One of the unwelcome side-effects that can occur during HDD is the uncontrolled fracture of the soil surrounding the newly created borehole. Known as hydraulic fracturing, loss of drilling slurry through rupture of the soil is affected by the pressures of the drilling slurry used in the construction process. It can result in effects to adjacent infrastructure as well as serious environmental damage due to contamination of nearby waterways. Since its effect on the surrounding, or "host", soil is not well understood, a comprehensive knowledge is needed concerning the effect on hydraulic fracture of the critical drilling slurry pressures and properties of the host soil material.

The drilling slurry can be used for cleaning and cooling of the drill-head and stabilization of the borehole, but its primarily role is the transport of bore cuttings back to the surface through the induction of a pressure gradient (Duvestyn et al. 2001). To better understand the magnitudes of these induced slurry pressures critical for hydraulic fracture at various construction depths and conditions, the finite element method was used to analyze the stresses in the soil surrounding a 0.2 metre diameter conduit.

Because the length of an HDD installation is considerably larger than the diameter of the borehole, the problem can be simplified to two-dimensional plane-strain conditions. The modeled drilling process did not simulate the actual, more complex, three-dimensional cutting done by the drill head. Instead, a simplified two-dimensional process that suited the plane-strain conditions was used with the focus placed on the magnitudes and application of the drilling slurry pressures in the borehole. Finite element analysis of the problem reported by Kennedy et al. (2004) shows that a linear elastic response of the host soil is effectively represented by elastic plate theory (Obert and Duval 1967). When the host soil has a coefficient of lateral earth pressure at rest (K_0) value less than unity, the tangential stress (σ_θ) at the soil-borehole boundary critical for hydraulic fracture will occur at the crown or invert. Similarly, the critical tangential stress will occur at the springline when the soil has a K_0 value greater than unity. Hydraulic fracture was considered to have occurred in the analyses when this tangential stress reduced far enough to reach the tensile strength of the soil. An increase in the internal pressure (P_i) in the hole will cause an equal reduction of the tangential stress and therefore the tangential stress at the crown or invert of an elastic plate with a circular hole is (Hefny and Lo 1992):

$$\sigma_\theta = 3\sigma_x - \sigma_y - P_i \quad [1]$$

An equation defining the limiting (or maximum allowable) drilling slurry pressure (P_{max}) has been developed at the Delft University of Technology (Arends 2003). For cohesive soil with an undrained cohesive strength (c_u) and a friction angle of zero, the equation simplifies to:

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

where σ_0 is the initial overburden stress of the soil.

Kennedy et al. (2004) examined the relationship between drilling slurry pressures and the elastic response of the host soil when there was no shear failure. They found that elastic theory (Equation 1) provides reliable predictions of the tangential stresses at the borehole crown. The present study uses finite element analyses to demonstrate this relationship and examine the onset of tensile fracture in an elasto-plastic host soil when exhibiting either a linear or non-linear response.

2. PLASTICITY THEORY REVIEW

When there is plastic yielding in the finite element analyses and the response of the soil is no longer linear, the stresses in the soil are compared to the Mohr-Coulomb failure criterion (Holtz and Kovacs 1981). For a cohesive material, when an undrained cohesive strength and a friction angle of zero are used, the Mohr-Coulomb failure criterion simplifies to the shear strength being equal to the undrained cohesion (Figure 1).

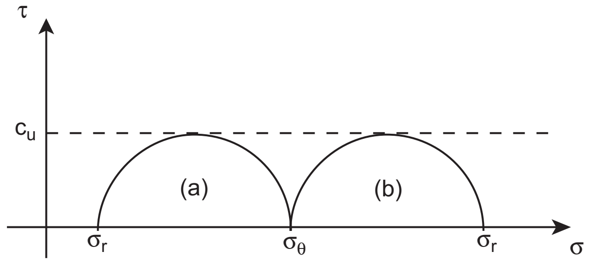

Figure 1 Mohr-Coulomb failure plot for undrained material.

At the borehole periphery, the radial stress (σ_r) is equal to the pressure inside the borehole. Additionally, the major and minor principal stresses are equal to the tangential or radial stress – depending on the stress situation. When the internal pressure is very small, the major and minor principal stresses are equal to the tangential and radial stresses, respectively (Figure 1a); when the internal pressure is very large, the major and minor principal stresses are equal to the radial and tangential stresses, respectively (Figure 1b). Therefore, the Mohr-Coulomb failure criterion for an undrained material can be written as:

$$\sigma_\theta = \sigma_r + 2c_u \quad \text{(for } \sigma_r < \sigma_\theta\text{)} \quad [3a]$$

$$\sigma_\theta = \sigma_r - 2c_u \quad \text{(for } \sigma_r > \sigma_\theta\text{)} \quad [3b]$$

It is important to note that when the internal pressure in the borehole is substituted for σ_r in these formulae, they only describe the tangential stress in the soil *at the crown of the borehole* once it has yielded. They do not represent the tangential stress in other yielded areas of the soil remote from the borehole.

3. NUMERICAL MODEL

The elastic plate theory (Equation 1) and the equation developed at the Delft University of Technology (Equation 2) are based on a number of approximations including the assumption that the host material is isotropic, and the exclude the effects of gravity creating gradients of soil pressures and drilling slurry pressures with depth (Arends 2003, Obert and Duval 1967). The numerical model used for the analyses reported here is similar to the one described by Kennedy et al. (2004) which does not rely on these assumptions. The finite element model enables the examination of their influence on the problem.

A suitable finite element mesh was developed to model directional drilling of the 0.2 metre diameter borehole and provide reliable calculations of the stresses around the newly created conduit. A total of 2404 six-noded triangular elements are used to model the two-dimensional plane-strain problem. Elasto-plastic constitutive behaviour satisfying the Mohr-Coulomb failure criterion is employed for all soils. As shown in Figure 2, the mesh becomes finer near the circular area to be excavated to form the borehole. A uniformly distributed load is applied to the top of the mesh and can be scaled to represent the effects of various heights of soil above the borehole and enables analysis of construction at different depths. The initial geostatic pressures are calculated using this uniformly distributed load, the unit weight of the soil (γ_{soil}) and the coefficient of lateral earth pressure at rest. Since the top of the mesh is located a sufficient distance above the borehole (five diameters), the stiffness of the soil above the top of the mesh is neglected without affecting the soil stresses around the borehole (Kennedy 2004). Additionally, none of the plastic zones are any closer than a borehole diameter from the boundaries.

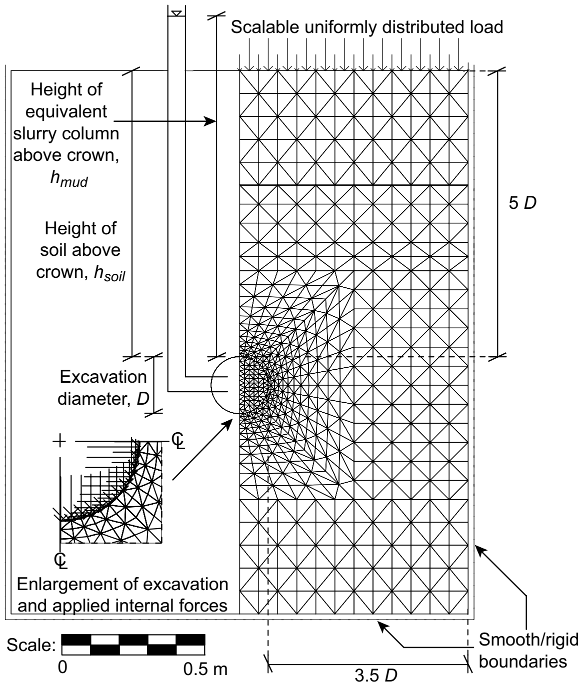

Figure 2 Example mesh and parameter definition.

Because every physical aspect of the drilling process can not be incorporated into the model (e.g. interaction of drill-head and host soil, soil cutting, and mixing of soil cuttings with drilling slurry), a simplified representation of the process is used. Focus is placed on the drilling slurry pressures once the slurry is present in the newly drilled cavity. The drilling slurry pressure is introduced while the pressure due to the existing soil is simultaneously reduced. The resulting stress path is a linear change from the in-situ soil stresses to the final drilling slurry design pressure. Since the borehole is never empty in the construction process, this procedure employs a simple stress path that represents the combined removal of the host soil and application of the slurry pressures.

A separate finite element analysis is used to calculate the nodal forces that would simulate the pressure due to the existing soil at the borehole annulus. The initial geostatic conditions are modeled and the forces are calculated by evaluating the normal reactions in the annulus of the excavated area. A similar analysis is used to estimate the forces that would simulate the final drilling slurry pressure; however the unit weight of the slurry (γ_{mud}) is used in conjunction with a horizontal to vertical stress ratio of unity. By separating forces that simulate pressure due to the slurry's fluid gradient in the borehole, the drilling slurry pressures are simply and reliably scaled to simulate stress paths that start at the pressure in the borehole due to the existing soil and end at any prescribed drilling slurry pressure (Kennedy 2004).

The model simulates drilling of the 0.2 metre diameter borehole at depths of two and five metres below the ground surface. The host soil is assumed to be undrained clay with a unit weight of 16 kilonewtons per cubic metre. The drilling slurry is assumed to have a unit weight of 13 kilonewtons per cubic metre (Andersen et al. 1994). Analyses are performed with the lateral earth pressure coefficient equal to 0.6, 0.9, and 1.11 to investigate the effect of different initial horizontal earth pressures. In order to examine the effect of the soil's strength, the undrained cohesion is varied from that of soft clay, 20 kilopascals, to that of very stiff clay, 150 kilopascals (Canadian Geotechnical Society 1992). The undrained elastic modulus is chosen in relation to the undrained cohesion (Electric Power Research Institute 1990) to maintain a realistic model; however it has little effect on the response of the soil stresses. Because the permeability of the clay is expected to be low, the soil is modeled as an incompressible solid, and a Poisson's ratio of 0.5 was selected. In order to avoid numerical instability, a value of 0.499 is used in the analyses. The parameters used in the model are outlined in Table 1.

Even though the analyses presented here only considered a borehole with a diameter of 0.2 metres, the research applies to construction with other borehole diameters. When the critical soil response is at the crown, the borehole diameter has no effect on the magnitude of the stresses critical to the problem. When the critical soil response is elsewhere (at the springline) the diameter of the borehole only affects the initial overburden stress at the location and is considered in the correlating theory.

Table 1 Model parameters for clay host soil model.

Borehole Diameter, *D*	0.2 m
Construction Depth, h_{soil}	2 m, 5 m
Soil Unit Weight, γ_{soil}	16 kN/m^3
Drilling Slurry Unit Weight, γ_{mud}	13 kN/m^3
Lateral Earth Pressure Coefficient at Rest, K_0	0.6, 0.9, 1.11
Undrained Cohesion, c_u	20 – 150 kPa
Undrained Elastic Modulus, E_u	1.6 – 18 MPa
Poisson's Ratio, ν_u	0.499

4. FINITE ELEMENT ANALYSIS RESULTS

4.1 Model Evaluation

The model's effectiveness was evaluated in multiple steps through comparisons with the elastic plate theory (Kennedy 2004). First, the model was simplified to the conditions under which the elastic plate theory is defined. The fixed boundaries on the sides and bottom of the mesh were removed and replaced with uniformly distributed loads. The K_0 value was set to unity and the unit weight of the soil was set to zero to ensure there were no stress gradients with depth. Second, the uniformly distributed loads along the edges of the mesh were replaced with smooth, rigid boundaries and the K_0 was set to a value less than 1.0. The unit weight of the soil was maintained at zero to ensure no gradients of stress with depth. A uniformly distributed load along the top of the mesh was used to induce the prescribed stresses. Finally, the unit weight of the soil was included in the model. Since the stresses vary with depth in this scenario, the elastic plate theory was calculated with the vertical and horizontal stresses that occur at the depth of the crown of the cavity.

The differences between each of the three analyzed steps described above and the elastic plate theory were calculated to examine the performance of the finite element model. The difference at the crown of the cavity ranged from 0.3 % in the first analysis, to 4.2 % in the third analysis, as discussed by Kennedy et al. (2004). Since the finite element mesh does not have integration points along the vertical axis of the cavity, these differences are not expected to be zero. Further, differences are expected for the third case relative to the elastic plate theory employing uniform initial stress. With this in mind, the finite element model's results are considered very acceptable in comparison to the closed form elastic plate theory solution. Further comparison to the elastic plate theory as well as successful comparison to elasto-plastic theory is presented in the following sections.

4.2 Review of Purely Elastic Response

The drilling slurry pressure was varied to calculate the response of stresses in the surrounding host soil. The resulting tangential stresses at the crown of the borehole were compared to the tangential stresses calculated by elastic plate theory (Equation 1). In all analyses, the finite element calculation followed the elastic plate theory when there was no shear failure of the soil. As expected, an increase in the drilling slurry pressure results in an equal decrease in the tangential stress at the crown (Equation 1). When the tensile strength of the soil is conservatively assumed to be zero, Equation 1 can be rearranged and the maximum allowable drilling slurry pressure for soil with a K_0 value less than unity can be calculated in terms of the initial overburden stress at the crown,

$$P_{\max} = \sigma_0(3K_0 - 1) \quad \text{(for } K_0 < 1\text{)} \qquad [4a]$$

Similarly, the maximum allowable drilling slurry pressure can be calculated in terms of the initial overburden stress at the springline (σ_{sp}) when K_0 is greater than unity,

$$P_{\max} = \sigma_{sp}(3 - K_0) \quad \text{(for } K_0 > 1\text{)} \qquad [4b]$$

An increase in the K_0 value of the soil when it is less than unity increases the initial horizontal stresses, and therefore increases the tangential stress at the crown of the borehole. Thus, the maximum allowable drilling slurry pressure also increases (Equation 4a). An increase in the K_0 value of the soil when it is greater than unity also increases horizontal stresses, but consequently decreases the tangential stress at the springline of the borehole. In this case, the maximum allowable drilling slurry pressure decreases (Equation 4b).

However, the elastic plate theory only applies when there is no shear failure of the host soil. The upper and lower bounds of drilling slurry pressures where the elastic plate theory is effective can be defined in terms of the undrained cohesion of the soil for K_0 values less than unity. Similar theory can also be applied for soils with K_0 values greater than unity.

4.3 Elasto-plastic Response

When the drilling slurry pressures rise above or fall below the bounds defining the purely elastic response, plastic yielding of the host soil was observed in the finite element model. Calculations based on the Mohr-Coulomb failure criterion provide tangential stresses at the crown or springline of the borehole following yielding that agree with the calculated finite element results. Equation 3a describes the tangential stress at the crown for very small drilling slurry pressures when yielding occurs as a result of a collapse of the borehole, or "plastic collapse". Similarly, Equation 3b describes the tangential stress at the crown for very large drilling slurry pressures when the yielding occurs as a result of "plastic expansion" of the borehole.

For a construction at a depth of five metres in a soft soil (c_u = 20 kPa) with a K_0 value of 0.9, Figure 3 shows a plot of the tangential stress at the crown of the borehole at different final drilling slurry pressures and compares the values calculated by elastic plate theory (Equation 1) and plasticity theory with a Mohr-Coulomb failure criterion (Equations 3a and 3b) against the finite element results. Between the drilling slurry pressures of approximately 50 kilopascals and 85 kilopascals, Figure 3 illustrates the elastic response of the soil due to an increase in drilling slurry pressure: a reduction in tangential crown stress. Once yielding occurs in the host soil at the borehole annulus, the tangential stress no longer decreases. As the drilling slurry pressure is increased further, the tangential crown stress begins to increase, as predicted by the plastic expansion theory. For example, the soil used in Figure 3 would exhibit elastic behaviour from medium drilling slurry pressures up to a pressure of 88 kilopascals where it would exhibit its lowest tangential crown stress of 48 kilopascals. Once drilling slurry pressures higher than 88 are used, plastic yielding occurs at the crown and the tangential stresses become larger than 48 kilopascals. Therefore, hydraulic fracture can only occur when the host soil exhibits a purely elastic response at the crown. If it does not occur when the response is elastic, it should not occur when the response is elasto-plastic.

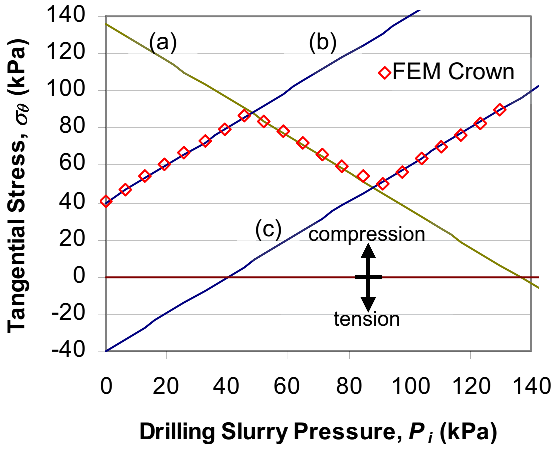

Figure 3 Plot of tangential crown stress at different final drilling slurry pressures for a) elastic plate theory (Equation 1); plasticity theory: b) collapse (Equation 3a) and c) expansion (Equation 3b); and finite element analyses of soft clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.9, c_u = 20 kPa, γ_{mud} = 13 kN/m^3).

Higher values of undrained cohesion – such as those for stiffer clays – will shift the line in Figure 3 defined by Equation 3a up and the line defined by Equation 3b down (Figure 4). Similarly, lower values of K_0 will shift the line in Figure 3 defined by Equation 1 down (Figure 4). The soils with these higher undrained cohesion strengths will have a larger range of drilling slurry pressures that will still produce an elastic response. If this range is large enough, increased drilling slurry pressures decrease the tangential crown stress to the tensile strength of the soil and hydraulic fracture can occur. The maximum allowable drilling slurry pressure (P_{max}) would then be defined by Equation 4a. Therefore, stiffer clays are more vulnerable to true hydraulic fracture; however they may be less susceptible to slurry loss due to other, as yet undefined, mechanisms.

Figure 5 compares the maximum allowable drilling slurry pressure at initiation of hydraulic fracture with different lateral earth pressure coefficients for a firm clay soil (c_u = 40 kPa) at a construction depth of five metres. At lower values of K_0 (less than 0.67) where there is less horizontal confining pressure and the soil at the crown of the borehole remains elastic, P_{max} can be calculated using Equation 4a. Similarly, at very high values of K_0 (greater than 2.0), the soil at the springline remains elastic and P_{max} can be calculated using Equation 4b. When the K_0 value is between 0.67 and 2.0 for this firm clay, the soil at the crown of the borehole begins to yield before tangential stress reduces below the soil's assumed tensile strength of zero. Therefore, for a K_0 between 0.67 and 2.0, hydraulic fracture can no longer occur. Above the dotted line representing Equations 4a and 4b, the soil at the borehole crown would have yielded due to plastic expansion. Below this line the soil either exhibits elastic response or it yields due to plastic collapse of the borehole – in each case, the tangential stresses at the crown never reduce below zero.

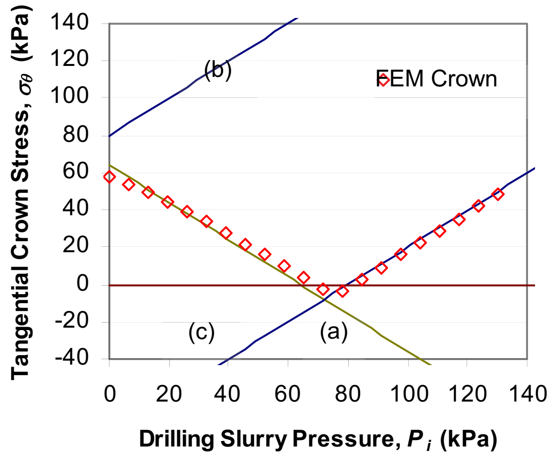

Figure 4 Plot of tangential crown stress at different final drilling slurry pressures for a) elastic plate theory (Equation 1); plasticity theory: b) collapse (Equation 3a) and c) expansion (Equation 3b); and finite element analyses of firm clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.6, c_u = 40 kPa, γ_{mud} = 13 kN/m^3).

Figure 5 has been presented to illustrate the mathematical relationship between the K_0 value of the soil and the theoretical maximum allowable drilling slurry pressure. It is important to note that it is not meant to represent a typical range of K_0 values for firm clay.

During the construction process using a drilling slurry pressure high enough to induce plastic expansion of the soil, the yielded zone begins at the crown of the borehole after the initial elastic response and expands towards the ground surface. At the start of the process the soil response is elastic and the tangential stress at the crown of the borehole decreases (in accordance with Equation 1). Once yielding begins at the crown, further increases in slurry pressure result in increases in the size of the plastic zone. The point of minimum circumferential stress moves away from the crown towards the ground surface , and the tangential stress at the crown increases (in accordance with Equation 3b). Figure 6 compares tangential stress above the crown with the plastic zone for a firm clay soil (c_u = 40 kPa) with a K_0 value of 0.9.

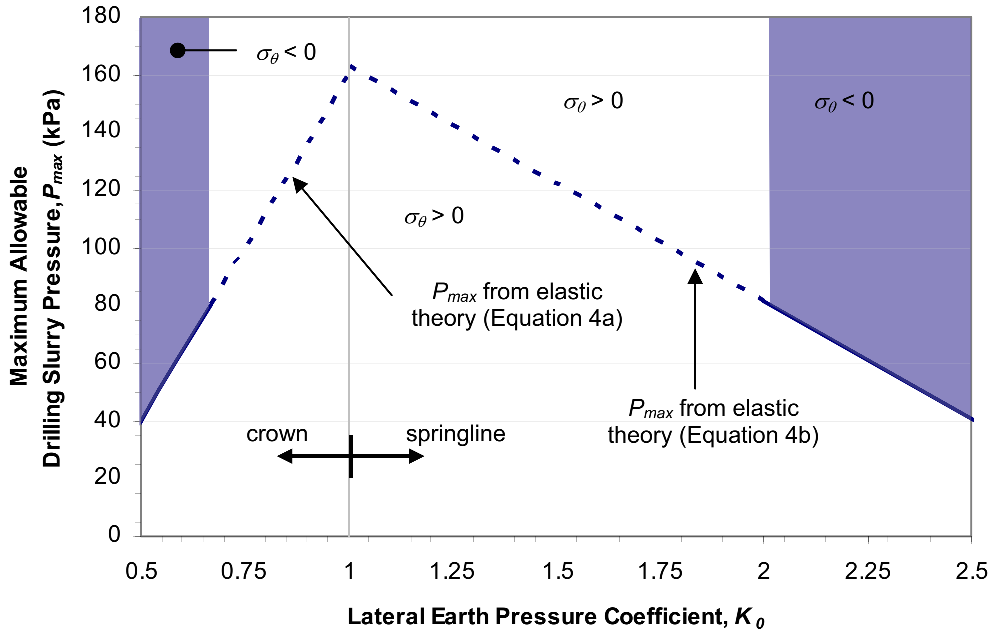

Figure 5 Maximum allowable drilling slurry pressure as defined by Equation 4 for firm clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, c_u = 40 kPa).

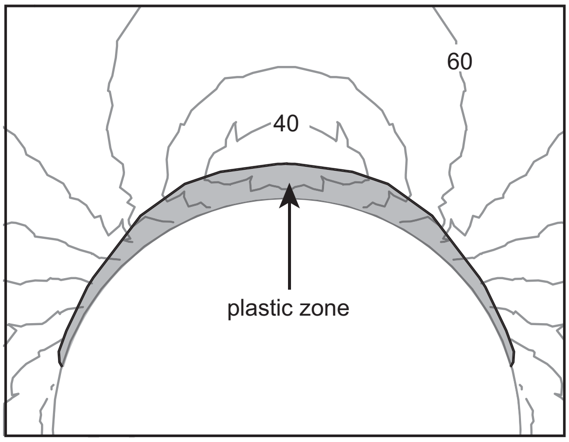

Figure 6 Contours of horizontal stress (kPa) and limit of plastic zone at conduit crown (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.9, c_u = 40 kPa, γ_{mud} = 13 kN/m^3, P_i = 125 kPa).

The analysis results shown in Figure 7 illustrate the change in magnitude and location of the minimum tangential stress with different drilling slurry pressures soil for a construction at a depth of five metres and a soil with a K_0 of 0.9 and an undrained cohesion of 20 kilopascals. Between the pressures of approximately 50 kilopascals and 85 kilopascals where the soil response is elastic, the minimum tangential stress varies and occurs at the crown.

With slurry pressures above 85 kilopascals, the minimum tangential stress remains at approximately 50 kilopascals and occurs at the limit of the plastic zone, some distance directly above the crown as discussed above. This distance increases as the plastic zone enlarges with increased slurry pressure.

It is important to note that Equation 5a calculates the minimum tangential stress above the crown *within the zone of influence around the borehole*. That is, further above the borehole where the drilling process has much less effect on the stresses in the soil, the tangential stress will reduce due to the geostatic gradient. Equation 5a predicts the tangential stress in the soil near the borehole that is significantly influenced by the construction.

Throughout the simulated construction process based on steadily increasing slurry pressures, the minimum tangential stress above the crown occurs at the crown of the borehole where the soil response is elastic, and moves with the highest point of the plastic zone towards the ground surface when soil response is elasto-plastic. The minimum stress above the crown at the edge of the plastic zone is then equal to the tangential stress at the crown just prior to plastic yielding. For soils that do not produce a hydraulic fracture, the minimum tangential stress above the crown is equal to:

$$(\sigma_\theta)_{\min} = \tfrac{1}{2}\sigma_0(3K_0 - 1) - c_u \quad \text{(for } K_0 < 1\text{)} \qquad [5a]$$

and near the springline:

$$\left(\sigma_\theta\right)_{\min} = \tfrac{1}{2}\sigma_{sp}(3 - K_0) - c_u \quad \text{(for } K_0 > 1\text{)} \qquad [5b]$$

Therefore, with tension defined as negative,

- if $(\sigma_\theta)_{min}$ is greater than the tensile strength of the soil, hydraulic fracture will not occur;
- if $(\sigma_\theta)_{min}$ is less than the tensile strength of the soil, hydraulic fracture will occur with a drilling slurry pressure as calculated by Equation 4a or 4b.

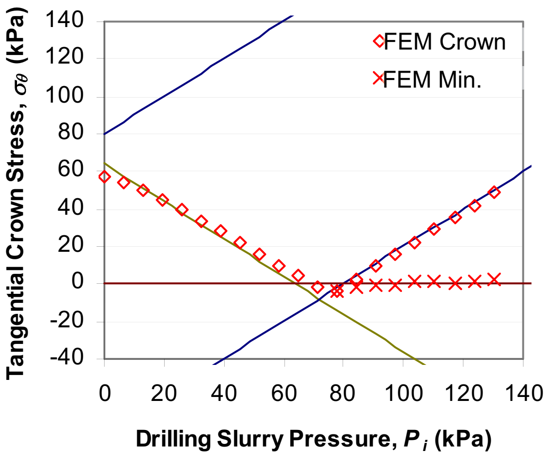

Figure 7 Plot of tangential crown stress and minimum tangential stress above crown at different final drilling slurry pressures for elastic plate theory, plasticity theory, and finite element analyses of soft clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.6, c_u = 40 kPa, γ_{mud} = 13 kN/m^3).

5. SUMMARY

Hydraulic fracturing is a consequence of Horizontal Directional Drilling that has often been encountered and can lead to loss of drilling efficiency, damage of nearby infrastructure, and costly environmental damage. Unfortunately, the phenomenon is not well understood. A design equation has been developed (Arends 2003) to predict the maximum allowable drilling fluid pressure that is currently being used in the design of these drilling projects. Based on cavity expansion theory, this equation calculates the limiting pressure in terms of a plastic zone surrounding the borehole. However, it does not consider the coefficient of lateral earth pressure at rest (K_0), the tensile strength of the soil, or gradients of stress with depth due to gravity. Furthermore, it focuses on a failure mechanism that does not involve soil fracture. Instead, it seeks to evaluate the development of unconfined plastic flow of the soil.

A finite element model was used to examine hydraulic fracture and the elasto-plastic conditions critical for its presence when drilling through clay soil. Analyses performed with the model were used to study the reliability of elastic plate theory and plasticity theory with a Mohr-Coulomb failure criterion to predict the drilling slurry pressures that lead to tensile failure of the surrounding soil. A parametric study examined the tangential stresses surrounding a 0.2 metre diameter borehole in an undrained clayey soil with K_0 values of 0.6 0.9, and 1.11 at construction depths of two and five metres over a typical range of drilling slurry pressures. Focus was placed on the tangential stresses at the crown of the borehole for cases where K_0 was less than unity since these would be the smallest tangential stresses due to the increase of geostatic stresses with depth, and at the springline for cases where K_0 was greater than unity. Tangential crown stresses were examined using the finite element model as well as elastic plate theory and plasticity theory satisfying the Mohr-Coulomb failure criterion.

The elastic plate theory accurately calculated the tangential crown and springline stress when the soil responded elastically and predicted the decrease in tangential crown stress that resulted from an increase in drilling slurry pressures (P_i, Equation 1). The plasticity theory accurately calculated the tangential stresses once the soil at the crown or springline had yielded. Following yield, an increase in the drilling slurry pressure resulted in an increase in the tangential stress (Equation 3b). This increase in stress following yielding illustrates that hydraulic fracture associated with tensile rupture of the soil is no longer an issue once plastic yielding has occurred at the crown or springline of the borehole. Equation 5a and 5b describe the tangential stress at the crown or springline, respectively, when yielding begins, $(\sigma_\theta)_{min}$. If this value is greater than the tensile strength of the soil, hydraulic fracturing will not occur in the soil; if this value is less than the tensile strength of the soil, hydraulic fracturing will occur at some limiting drilling slurry pressure (P_{max}) that can be calculated using Equation 4a or 4b.

Therefore, soft clays pose little threat of hydraulic fracture since they yield well before stiffer clays would and do not have a chance to develop elastic tensile failure. However, it is important to note that other types of failure that involve loss of drilling slurry may be related to the plastic yielding of the surrounding soil due to cavity expansion. Occurrence of these mechanisms in the field may be classified as hydraulic fracture by contractors and further study is warranted.

6. ACKNOWLEDGEMENTS

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