Limiting Slurry Pressures to Control Hydraulic Fracturing in Directional Drilling Operations in Purely Cohesive Soil

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Hydraulic fracturing during horizontal directional drilling can permit drilling mud to travel to the ground surface, to collect under overlying pavements, or to be released into the riverbed during river crossings. These events can decrease drilling efficiency, damage adjacent infrastructure, and cause environmental damage. Current design equations for maximum drilling pressure focus on shear failure around the borehole drilled to house the new pipe. The present research examines, instead, the potential for tensile fracture of cohesive soils surrounding the borehole. Two-dimensional nonlinear finite element modeling is used to study the effectiveness of closed-form solutions for calculation of the drilling slurry pressures that fracture the surrounding soil. Tangential stresses are calculated for a borehole with a 0.2-m diameter in an undrained clay soil with various K_0 values, construction depths, and drilling slurry pressures. Elastic plate theory is found to provide effective values of (*a*) tangential crown and spring line stresses when the soil responds elastically and (*b*) the decreases in tangential crown stress that occur as drilling slurry pressures increase. Closed-form plasticity solutions provide good values of tangential stresses once the soil yields. Following yield, increases in mud pressure result in increases in tangential stress, so hydraulic fracture from tension is no longer an issue. The study indicates that mud loss in low-strength clays or those with K_0 close to unity is most likely the result of unconfined plastic flow (blowout). Mud loss for stiff clays and those with other K_0 values is more likely the result of tensile fracture.

The realization 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 favor of these newer construction techniques, which are consistently less disruptive and more cost-effective (*1*). 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 water and gas supply pipes and sewer or wastewater pipes, in areas that would not be suitable for a cut-and-cover installation, beneath a highway or river, for example. However, 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 slurry used in the construction process. Hydraulic fracturing can result in effects on adjacent infrastructure as well as serious environmental damage due to contamination of nearby waterways. Because its effect on the surrounding (or host) soil is not well understood, it is necessary to have comprehensive knowledge about both the effect on hydraulic fracture of the critical drilling slurry pressures and the properties of the host soil material.

The drilling slurry can be used for cleaning and cooling of the drill head and stabilizing of the borehole, but its primary role is the transport of bore cuttings to the surface through induction of a pressure gradient (*2*). To understand better the magnitudes of these induced slurry pressures that are critical for mud loss at various construction depths and conditions, the finite element method was used to analyze the stresses in clay soil surrounding a conduit with a 0.2-m diameter. Mud loss can result from either unconfined plastic flow (or blowout) of the soil surrounding the borehole, Figure 1*a*, or tensile fracture of the soil, Figure 1*b*. This second mechanism is the primary focus of this analysis. Mud loss when one is drilling through sand is complicated by the development of mud cake around the borehole and is investigated elsewhere (*3*).

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. This analysis is not, therefore, a detailed simulation of the complex, three-dimensional cutting processes at the drill head. The plane strain approximation is similar to that used in tunnel engineering for some decades, and it can be expected to be extremely successful unless mud loss occurs directly at the face as the tunnel is excavated. Finite element analysis of the problem (*4*) shows that a linear elastic response of the host soil is effectively represented by elastic plate theory (*5*). 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 spring line when the soil has a K_0 value greater than unity. Hydraulic fracture is considered to occur in the analyses when this tangential stress decreases 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 σ_θ, and therefore the tangential stress at the crown or invert of an elastic plate with a circular hole is as shown by Equation 1 (*6*):

$$\sigma_\theta = 3\sigma_x - \sigma_y - P_i \quad (1)$$

where σ_x and σ_y are the initial horizontal and vertical earth pressures, respectively, before drilling.

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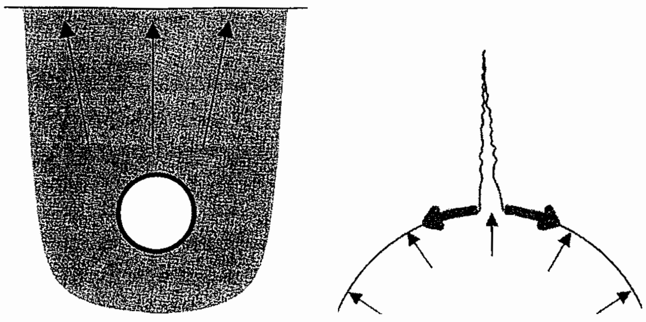

(a) (b)

FIGURE 1 Two failure mechanisms resulting in loss of drilling mud during directional drilling: (*a*) blowout (unconfined plastic flow) and (*b*) tensile fracture.

An equation defining the limiting (or maximum allowable) drilling slurry pressure (P_{max}) has been developed at the Technical University of Delft (*7*). For cohesive soil with cohesive strength *c*, friction angle of ϕ, and shear modulus *G*, P_{max} is calculated as shown in Equation 2:

$$P_{max} = [\sigma_0 (1 + \sin\phi) + c\cos\phi]\left[\left(\frac{a}{R_p}\right)^2 + Q\right]^{\frac{\sin\phi}{1+\sin\phi}} \quad (2)$$

where

σ_0 = initial vertical overburden stress of the soil,
a = borehole radius,
R_p = maximum distance that shear failure is allowed to extend beyond the borehole (typically one-half or two-thirds of the burial depth), and

$$Q = [\sigma_0(1 + \sin\ \phi) + c\ \cos\ \phi]/G$$

Kennedy et al. (*4*) 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) provided reliable values of the tangential stresses at the borehole crown before shear failure. The present study uses finite element analyses to demonstrate this relationship and examine the onset of tensile fracture in an elastoplastic host soil either a linear or a nonlinear response is exhibited.

REVIEW OF PLASTICITY THEORY

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 (*8*). 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 c_u (Figure 2).

At the borehole periphery, the radial stress (σ_r) is equal to the pressure inside the borehole. In addition, the major and minor principal stresses are equal to the tangential or radial stress, depending on the stress situation. When the internal pressure is extremely small, the major and minor principal stresses are equal to the tangential and radial stresses, respectively (Figure 2*a*); when the internal pressure is extremely large, the major and minor principal stresses are equal to the radial (σ_r) and tangential stresses, respectively (Figure 2*b*). Therefore, the Mohr–Coulomb failure criterion for an undrained material can be written as shown in Equations 3*a* and 3*b* (*8*):

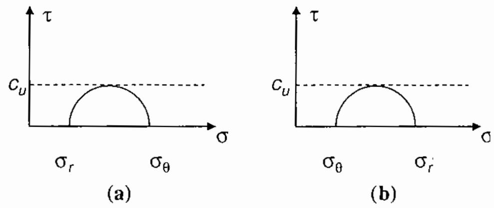

FIGURE 2 Mohr–Coulomb failure plot for undrained material: (*a*) borehole contraction and (*b*) borehole expansion.

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

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

When the internal pressure in the borehole is substituted for σ_r in these equations, they describe the tangential stress in the soil at the crown of the borehole once it has yielded. They do not, of course, represent the tangential stress in other yielded areas of the soil remote from the borehole.

NUMERICAL MODEL

The elastic plate theory (Equation 1) and the equation developed at the Technical University of Delft (Equation 2) are based on a number of approximations (including the assumption that the host material is isotropic), and they exclude the effects of gravity in creating gradients of soil pressures and drilling slurry pressures with depth (*5, 7*). The numerical model used for the analyses conducted in this paper is similar to the one described in Kennedy et al. (*4*), which does not rely on these assumptions.

A suitable finite element mesh was developed to model directional drilling of the borehole 0.2 m in diameter and to provide reliable calculations of the stresses around the newly created conduit. A total of 2,404 six-noded triangular elements were used to model the two-dimensional plane strain problem. Elastoplastic constitutive behavior satisfying the Mohr–Coulomb failure criterion was employed for all soils. As shown in Figure 3, the mesh became finer near the circular area to be excavated to form the borehole. A uniformly distributed load was applied to the top of the mesh and was scaled to represent the effects of various heights of soil above the borehole; it enabled analysis of construction at different depths. The initial geostatic pressures were calculated through use of this uniformly distributed load, the unit weight of the soil (γ_{soil}), and the coefficient of lateral earth pressure at rest. Boundary locations were chosen after numerical trials to demonstrate that changes in the boundary to positions farther from the borehole had a negligible effect on the results (*9*). For example, the top of the mesh was located a sufficient distance above the borehole (five diameters), so that the stiffness of the soil above the top of the mesh could be neglected without affecting the soil stresses around the borehole (*9*). In addition, all calculations reported here kept the zones of shear failure at least one borehole diameter from the boundaries.

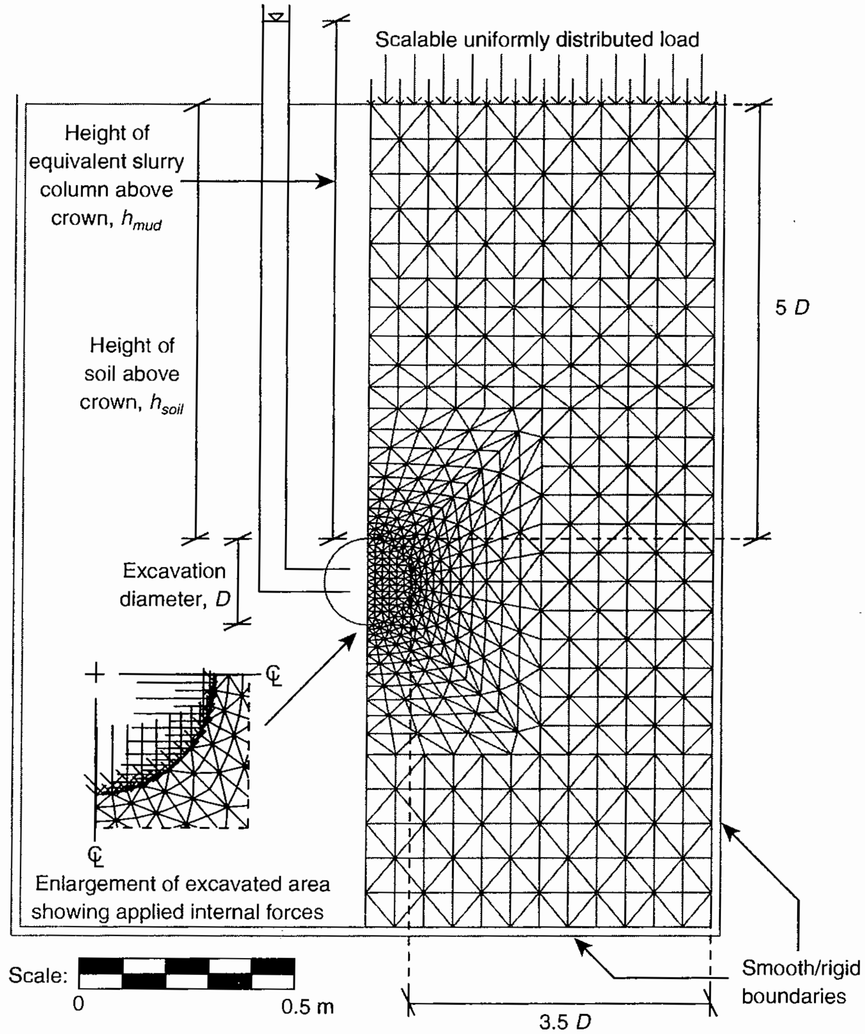

FIGURE 3 Example of mesh and definitions of parameters.

Because every physical aspect of the drilling process could 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 was used. Focus was placed on the drilling slurry pressures once the slurry was present in the newly drilled cavity. The drilling slurry pressure was introduced while the pressure caused by the existing soil was simultaneously reduced. The resulting stress path was a linear change from the geostatic soil stresses to the final drilling slurry design pressure. Because the borehole was never empty in the construction process, this procedure employed a simple stress path that represented the combined removal of the host soil and application of the slurry pressures.

A separate finite element analysis was used to calculate the nodal forces that would simulate the pressure caused by the existing soil at the borehole annulus. The initial geostatic conditions were modeled and the forces calculated by evaluation of the normal reactions in the annulus of the excavated area. A similar analysis was used to estimate the forces that would simulate the final drilling slurry pressure; however, the unit weight of the slurry (γ_{mud}) was used in conjunction with a horizontal-to-vertical stress ratio of unity. Through separation of the forces that simulate pressure due to the slurry's fluid gradient in the borehole, the drilling slurry pressures were simply and reliably scaled to simulate stress paths that started at the pressure in the borehole due to the existing soil and ended at any prescribed drilling slurry pressure (*9*).

The model simulated drilling of the borehole with the 0.2-m diameter at depths of 2 and 5 m below the ground surface. It was assumed that the host soil was to be undrained clay with a unit weight of 16 kN/m^3 and that the drilling slurry was to have a unit weight of 13 kN/m^3 (*10*). Analyses were 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. To examine the effect of the soil's strength, the undrained cohesion was varied from that of soft clay, 20 kPa, to that of extremely stiff clay, 150 kPa (*11*). The undrained elastic modulus was chosen in relation to the undrained cohesion (*12*) to maintain a realistic model; however, it had little effect on the response of the soil stresses. Because the permeability of the clay was expected to be low, the soil was modeled as an incompressible solid, and a Poisson's ratio of 0.5 was selected. To avoid numerical instability, a value of 0.499 was used in the analyses. The parameters used in the model are outlined in Table 1.

Even though the analyses presented here considered only a borehole with a diameter of 0.2 m, the conclusions are applicable to other borehole diameters (*9*). When the critical soil response is at the crown,

TABLE 1 Model Parameters for Clay Host Soil Model

Parameter	Value
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

the borehole diameter has no effect on the magnitude of the stresses critical to the problem. When the critical soil response is elsewhere (e.g., at the spring line), the diameter of the borehole is included in the calculation of the initial overburden stress.

RESULTS

Review of Purely Elastic Response

The drilling slurry pressure was varied to calculate the stresses in the surrounding host soil. The resulting tangential stresses at the crown of the borehole were compared with 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 resulted 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, as shown by Equation 4*a:*

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

Similarly, the maximum allowable drilling slurry pressure can be calculated in terms of the initial overburden stress at the spring line (σ_{sp}) when K_0 is greater than unity, as shown by Equation 4*b:*

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

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 4*a*). 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 spring line of the borehole. In this case, the maximum allowable drilling slurry pressure decreases (Equation 4*b*).

However, the elastic plate theory applies only 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. Bounds of this type are developed in a subsequent section for two cases: K_0 values of less than unity and K_0 values greater than unity.

Elastoplastic Response

When the drilling slurry pressures rose above or fell below the bounds that define the purely elastic response, shear failure of the host soil was observed in the finite element model. Calculations based on the Mohr–Coulomb failure criterion provide at the crown or spring line of the borehole tangential stresses following yielding that agree with the calculated finite element results. Equation 3*a* describes the tangential stress at the crown for extremely small drilling slurry pressures when the yielding occurs as a result of a collapse of the borehole (a plastic collapse). Similarly, Equation 3*b* describes the tangential stress at the crown for extremely large drilling slurry pressures when the yielding occurs as a result of plastic expansion of the borehole.

For a construction at a depth of 5 m in a soft soil (c_u = 20 kPa) with a K_0 value of 0.9, Figure 4 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)

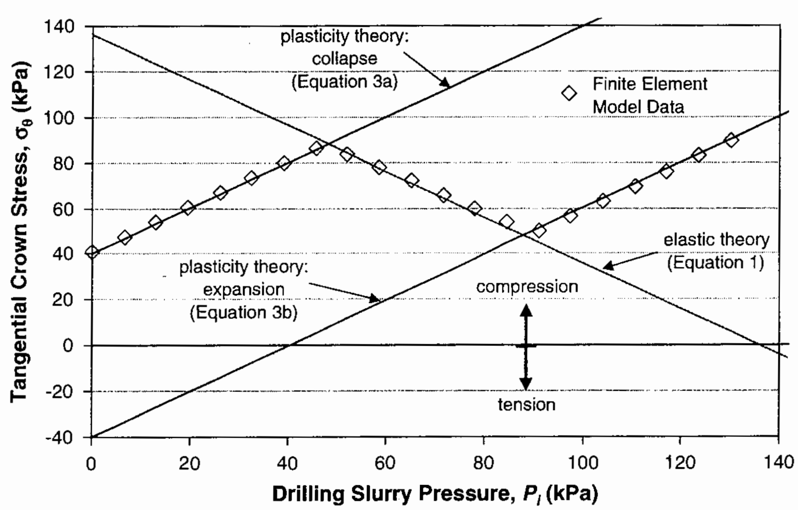

FIGURE 4 Plot of tangential crown stress at different final drilling slurry pressures for elastic plate theory, plasticity theory, and finite element analyses of soft clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.9, c_u = 20 kPa, γ_{mud} = 13 kN/m^3).

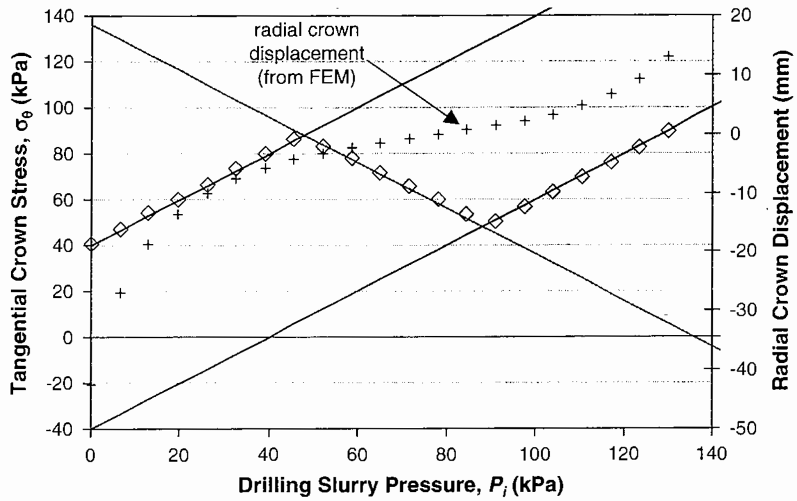

FIGURE 5 Comparison of tangential stress and radial displacement at crown for different final drilling slurry pressures (h_{soil} = 5 m, γ_{soil} = 16 kN/m³, K_0 = 0.9, c_u = 20 kPa, γ_{mud} = 13 kN/m³).

and plasticity theory with a Mohr–Coulomb failure criterion (Equations 3*a* and 3*b*) with the finite element results. For drilling slurry pressures between approximately 50 and 85 kPa, Figure 4 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, according to the limits of deviator stress defined in Equation 3*b*. For example, the soil used in Figure 4 would exhibit elastic behavior from medium drilling slurry pressures up to a pressure of 88 kPa, at which point it would exhibit its lowest tangential crown stress of 48 kPa. Once drilling slurry pressure higher than 88 was reached, shear failure of the soil at the crown resulted in tangential stresses that increased above 48 kPa. Therefore, tensile fracture could occur only when the host soil exhibited a purely elastic response at the crown. If it did not occur when the response was elastic, it should not occur when the response is elastoplastic.

Figure 5 illustrates the related radial displacements of the crown for the soil presented in Figure 4. When the soil response was elastic, the radial displacements increased linearly as final drilling slurry pressure increased. Once shear failure occurred in the soil, the ground stiffness progressively decreased, expanding the cavity as slurry pressure grew or contracting the cavity as slurry pressure decreased toward zero.

Higher values of undrained cohesion—such as those for stiffer clays—will shift the line in Figure 4 defined by Equation 3*a* up and the line defined by Equation 3*b* down (Figure 6). Similarly, lower values of K_0 will shift the line in Figure 4 defined by Equation 1 down (Figure 6). The soils with these higher shear 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 will 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

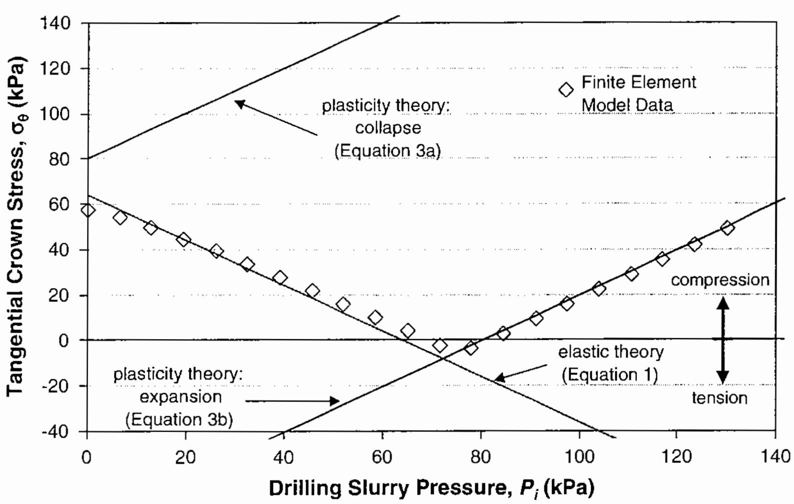

FIGURE 6 Plot of tangential crown stress at different final drilling slurry pressures for elastic plate theory, plasticity theory, and finite element analyses of firm clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m³, K_0 = 0.6, c_u = 40 kPa, γ_{mud} = 13 kN/m³).

Equation 4*a*. Therefore, stiffer clays are more vulnerable to tensile fracture, even though they are less susceptible to slurry loss as a result of blowout.

Figure 7 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 5 m. At lower values of K_0 (<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 with Equation 4*a*. Similarly, at extremely high values of K_0 (>2.0), the soil at the spring line remains elastic and P_{max} can be calculated with Equation 4*b*. 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 decreases below the soil's assumed tensile strength of zero. Therefore, for a K_0 between 0.67 and 2.0, hydraulic fracture cannot occur. Above the dotted lines in Figure 7 representing Equations 4*a* and 4*b*, the soil at the borehole crown would have yielded because of plastic expansion. Below these lines, the soil either exhibits elastic response or it yields from plastic collapse of the borehole; in each case, the tangential stresses at the crown never decrease below zero.

During construction that uses a drilling slurry pressure high enough to induce shear failure in the soil, the yielded zone begins at the crown of the borehole after the initial elastic response and expands toward the ground surface. Figure 8 shows the movement of the limit of this plastic zone as slurry pressures increase, for a borehole at a depth of 5 m through a firm clay ($c_u = 40$ kPa) with a K_0 of 0.9 and a final drilling mud slurry pressure of 125 kPa. 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 toward the ground surface (Figure 8), and the tangential stress at the crown increases (in accordance with Equation 3*b*). Figure 8*d* shows the limit of the plastic zone at the crown of the borehole once the slurry pressure reaches 125 kPa. If mud pressures were increased further, the zone of shear failure would eventually approach the ground surface and result in blowout.

Throughout the simulated construction process that was based on steadily increasing slurry pressures, the minimum tangential stress above the crown occurred at the crown of the borehole, where the soil response was elastic (Figure 8*a*), and moved with the highest point of the plastic zone toward the ground surface when soil response was elastoplastic (Figures 8*b*, 8*c*, and 8*d*). The minimum stress above the crown at the edge of the plastic zone was then equal to the tangential stress at the crown just before shear failure. Through use of the elastic solution to determine the in situ stresses at which deviator stress reaches twice the undrained cohesion, the minimum (least-compressive) tangential stress above the crown for soils that do not produce hydraulic fracture is then equal to

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

$$(\sigma_\theta)_{min} = \frac{1}{2}\sigma_0(3 - K_0) - c_u \qquad \text{for } K_0 > 1 \qquad (5b)$$

The results shown in Figure 9 illustrate the change in magnitude and location of the minimum tangential stress with different drilling slurry pressures for construction at a depth of 5 m and a soil with a K_0 of 0.9 and an undrained cohesion of 20 kPa. Between the pressures of approximately 50 and 85 kPa, where the soil response is elastic, the minimum tangential stress varies and occurs at the crown. With slurry pressures above 85 kPa, the minimum tangential stress remains at approximately 50 kPa and occurs at the limit of the plastic zone, some distance directly above the crown, as discussed above.

Equation 5*a* provides the minimum tangential stress above the crown within the zone of influence around the borehole. Further above the borehole, where the drilling process has less effect on the stresses in the soil, the tangential stress will decrease due to the geostatic gradient. Therefore, with tension defined as negative,

- If $(\sigma_\theta)_{min}$ is greater than the tensile strength of the soil, hydraulic fracture will not occur and
- 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 4*a* or 4*b*.

Fracture Initiation and Fracture Propagation

The finite element calculations presented here focus on initiation of tensile fractures. Once the fracture is initiated, its propagation is controlled by different processes.

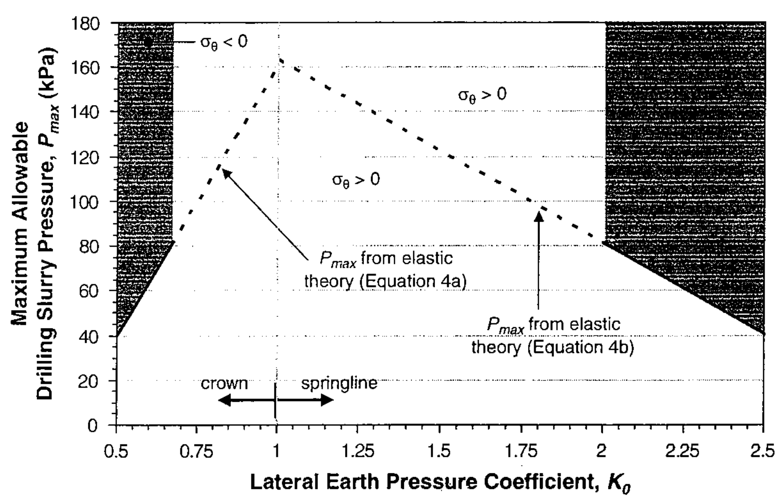

FIGURE 7 Maximum allowable drilling slurry pressure as defined by Equation 4 for firm clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m³, c_u = 40 kPa).

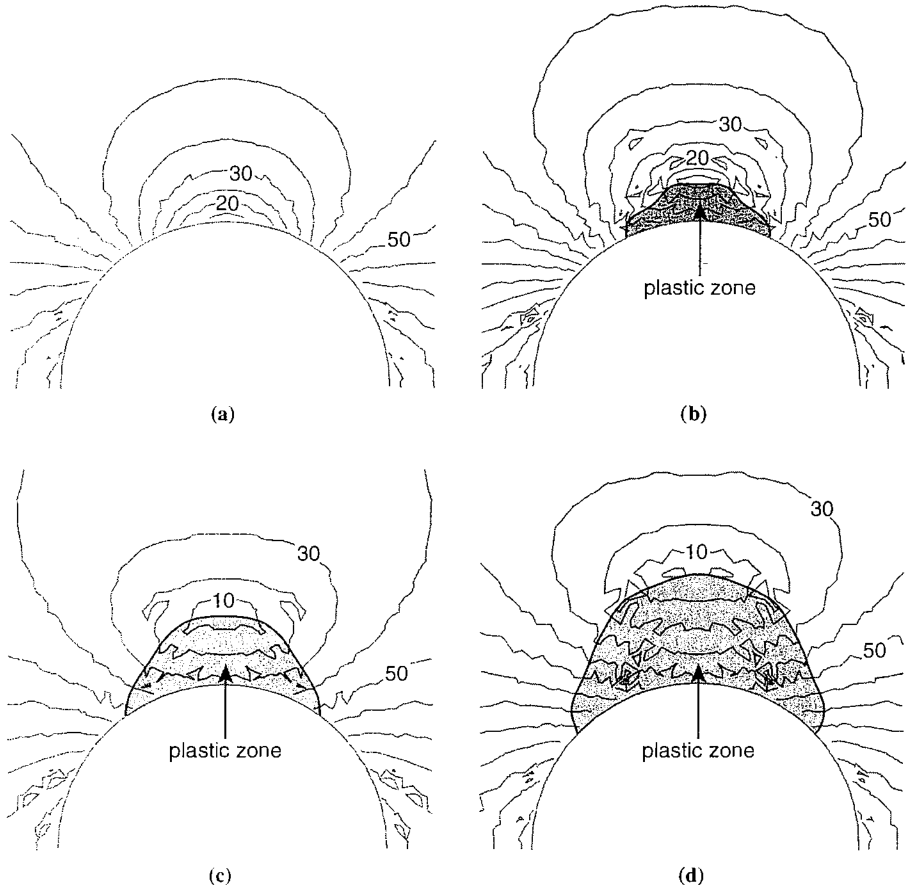

FIGURE 8 Contours of horizontal stress (kPa) and limit of plastic zone at conduit crown for percentage of construction completed (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.6, c_u = 40 kPa, γ_{mud} = 13 kN/m^3, P_i = 125 kPa): (*a*) 38%, (*b*) 58%, (*c*) 78%, and (*d*) 100%.

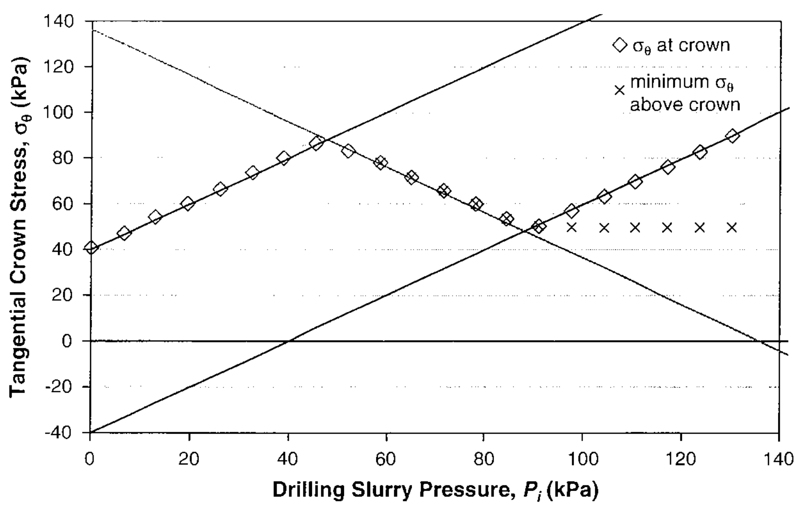

FIGURE 9 Plot of tangential crown stress and minimum tangential stress above crown at different final drilling slurry pressures for elastic plate theory, plasticity theory, and finite element analyses of soft clay soil (h_{soil} = 5 m, γ_{soil} = 16 kN/m^3, K_0 = 0.9, c_u = 20 kPa, γ_{mud} = 13 kN/m^3).

Fracture propagation in elastic solids is traditionally modeled by means of classical fracture mechanics. Propagation occurs when the Type I fracture energy integral K_I reaches or exceeds the fracture toughness (energy absorption potential) of the soil, K_c. Murdoch (*13*) has used these techniques to study fracture initiation and fracture propagation from vertical boreholes opened in clay. His work focuses on the artificial creation of fractures to facilitate contaminant extraction from clay strata. Substantial decreases in mud pressures occur after the initiation of fracture, and fracture propagation is largely controlled by the volume of fluid needed to open and extend the fracture. Fluid boundary conditions during directional drilling are distinctly different, however, since mud pressure is primarily controlled by the column of drilling fluid stretching through the borehole back to the ground surface. Fracture initiation, therefore, is likely followed by rapid fracture propagation under those sustained pressures. Prevention of fracture initiation appears to be the key to preventing hydraulic fracture during directional drilling.

Brief Comparison of the Two Failure Modes

Design Equation 2 presented by Arends (*7*) from the Technical University of Delft is currently used by many project designers to calculate the maximum allowable drilling slurry pressure for HDD installations. The equation is based on cavity expansion theory and calculates the limiting pressure in terms of a maximum allowable radius of the plastic zone surrounding the borehole. While it considers the cohesion and friction angle of the soil, it is based on a coefficient of lateral earth pressure at rest of unity.

Calculations for Equation 2 with $R_p/a = 6$ (this corresponds to the geometry in Figure 3, but is conservative for deeper systems) yield values of blowout pressures exceeding 200 kPa for a soil with $c_u = 40$ kPa. This is considerably higher than the tensile fracture solutions shown in Figure 7. Differences between blowout pressures calculated by use of Equation 2 and those for tensile fracture calculated by use of Equations 4*a* and 4*b* increase as the undrained shear strength grows. The blowout equation presented by Arends (*7*) does not cover the possibility that soils can respond elastically when $K < 1$ or $K > 1$, fracturing at much lower mud pressures. (The blowout equation produces neither valid nor conservative limits to drilling slurry pressures for control of tensile fracture.)

SUMMARY

Hydraulic fracturing is a consequence of HDD that has often been encountered and can lead to loss of drilling efficiency, disturbance to nearby infrastructure, and costly environmental damage. An equation developed at the Technical University of Delft is one procedure currently available for estimating maximum allowable drilling fluid pressures to prevent blowout (unconfined plastic flow of the soil) during drilling projects. However, this equation does not consider the possibility that the coefficient of lateral earth pressure K_0 is not equal to unity and that the soil can fail in tension.

A finite element model was used to examine tensile fracture and the elastoplastic 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 estimate the drilling slurry pressures that lead to tensile failure of the surrounding soil. A parametric study examined the tangential stresses surrounding a borehole 0.2 m in diameter in an undrained clayey soil with K_0 values of 0.6, 0.9, and 1.11 at construction depths of 2 and 5 m over a typical range of drilling slurry pressures. Focus was placed on the tangential stresses at the crown of the borehole for cases in which K_0 was less than unity (because these would be the smallest tangential stresses due to the increase of geostatic stresses with depth) and at the spring line for cases in which K_0 was greater than unity. Tangential crown stresses were examined through use of the finite element model as well as through elastic plate theory and plasticity theory satisfying the Mohr–Coulomb failure criterion.

The elastic plate theory successfully provides the tangential crown and spring line stresses when the soil responds elastically, and it gives the decrease in tangential crown stress that results from an increase in drilling slurry pressures (P_i, Equation 1). The plasticity theory solution provides the tangential stresses once the soil at the crown or spring line has yielded. After yield, an increase in the drilling slurry pressure results in an increase in the tangential stress. This increase in stress following shear failure of the soil reveals that hydraulic fracture associated with tensile rupture of the soil is no longer an issue once shear failure has occurred at the crown or spring line of the borehole.

Design equations were developed that provide the tangential stress at the crown or spring line, respectively, when yielding begins, $(\sigma_\theta)_{min}$. If this value is greater than the tensile strength of the soil (when a compression positive sign convention is used), hydraulic fracturing will not occur in the soil and a blowout solution should be employed; 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 by means of these design equations.

The analysis presented here indicates that stiff (overconsolidated) clays are more susceptible to tensile fracture than blowout, and extremely unconservative estimates of limiting mud pressure result from the use of the Delft equation for blowout. In contrast, it appears that soft clays pose little threat of tensile fracture as a result of borehole pressure, because they yield well before stiffer clays would and do not have a chance to develop elastic tensile failure. These materials are more vulnerable to blowout where loss of drilling slurry is related to shear failure of the surrounding soil and unconfined plastic flow.

Further study is required to assess whether the theoretical models for tensile fracture and blowout prove effective in controlling mud loss in the field. While there is a dearth of field data, work has begun to examine unpublished test data from the Technical University of Delft and to monitor drilling projects in North America. The objective is to use the theoretical framework described here to review and interpret those field observations, so that persuasive guidance can be provided to consultants and contractors.

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