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Practical criteria for assessment of horizontal borehole instability in saturated clay

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ABSTRACT

Horizontal borehole instability raises concern due to negative impacts on success of drilling, reaming and pipe installation during Horizontal Directional Drilling. Shear failure (blow-out) and tensile failure (hydraulic fracture) are the two main failure mechanisms controlling borehole instability in saturated clay. Criteria for categorizing shear failure versus tensile failure are given which are functions of the ratio of undrained shear strength to vertical effective stress S_u/σ_v' and the Lateral Earth Pressure Coefficient at Rest K_0'. Given that S_u/σ_v' and K_0' can be expressed as a function of soil parameters like friction angle, Over Consolidation Ratio (OCR) and Liquidity Index (LI), new forms of these criteria are developed for situations where S_u/σ_v' and K_0' cannot be obtained directly. It is confirmed that tensile failure generally controls in brittle clays like heavily overconsolidated and/or low liquidity index materials. Cases from the laboratory and the field as reported in the literature are used to examine the effectiveness of the new criteria, with inconsistency between theory and the physical evidence explained.

1. Introduction

Horizontal borehole stability is a key concern when Horizontal Directional Drilling (HDD) is used to install new pipelines below the ground surface. Bentonite or other drilling mud is used to balance external pressure around the borehole and to prevent its collapse (ASTM F1962-11). However, mud pressure should also be limited to preclude failures that can result from high mud pressure. Two main failure mechanisms are usually considered, i.e. shear failure and tensile failure. However, when these failure mechanisms are discussed (e.g. Bennett and Wallin, 2008; Staheli et al., 2010; Wallin et al., 2010 and Neher, 2013), "Hydrofracture" or "Hydraulic fracture" is often mentioned in relation to cavity expansion models like the so-called "Delft Equation" (Luger and Hergarden, 1988) that quantify how shear failure controls the maximum mud pressure (this approach continues to be used as the basis for standard NEN 3650-1 + C1 (2017), though the elastic-plastic 'cavity expansion' calculation discussed in that standard includes considerations of hoop strains rather than just the radial extent of shear failure addressed by Luger and Hergarden (1988). In the current paper, "Hydrofracture" or "Hydraulic fracture" will be used to refer to mud flow through tensile fractures in the soil around the borehole, while "blow-out" will be used to refer to loss of drilling mud due to shear failure of the soil around the borehole.

Most studies (e.g. Bjerrum et al., 1972; Massarsch, 1978; Jaworski et al., 1981; Mori and Tamura, 1987; Panah and Yanagisawa, 1989; Lo and Kaniaru, 1990; Lefebvre et al., 1991; Hefny and Lo, 1992; Murdoch, 1992a, 1992b, 1992c and Anderson et al., 1994) of tensile fracture in soil adjacent to boreholes have focused on vertical boreholes where confining stresses are uniform around the borehole (horizontal stresses are the same in all directions, i.e. axisymmetric). This is different from the case of a horizontal borehole because Lateral Earth Pressure Coefficient at Rest (K_0') in saturated clay is usually unlikely to be 1, and so stresses do vary around the circumference of a horizontal borehole (they are not axisymmetric). A few studies have examined hydraulic fracture beside horizontal boreholes. Wang et al. (2009) used numerical analysis to investigate crack initiation and propagation in a 2-D cylindrical cavity in heterogeneous stiff soils and Alfaro and Wong (2001) presented a laboratory experimental investigation on hydraulic fracturing. Kennedy (2004) and Kennedy et al. (2004) examined tensile failure in saturated clay during HDD. They explicitly considered K_0', and suggested that tensile fracture initiates when total circumferential stress around the borehole reaches zero (based on a conservative approach where the tensile strength of saturated clay is assumed to be zero).

Few research studies have explicitly considered the influence of Lateral Earth Pressure Coefficient at Rest K_0' on development of blow-out during HDD. Most papers (e.g. Bennett and Wallin, 2008; Staheli et al., 2010; Wallin et al., 2010 and Neher, 2013 and Rostami et al., 2015) from the trenchless industry still apply the "Delft Equation"

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Nomenclature

γ	soil unit weight
Δ	prefix denoting increment
θ	angle, start from 3 o'clock direction and rotate counter-clockwise
κ	recompression index in isotropic compression
Λ	plastic volumetric strain ratio
λ	compression index in isotropic compression
σ_0'	confining stress
σ_1	maximum principal stress
σ_1'	maximum principal effective stress
σ_3	minimum principal stress
σ_3'	minimum principal effective stress
σ_v	vertical total stress
σ_v'	vertical effective stress
σ_{vc}'	preconsolidation effective vertical stress
σ_{vo}'	current effective vertical stress
σ_h	horizontal total stress
σ_h'	horizontal effective stress
σ_{h1}'	horizontal effective stress in direction 1
σ_{h2}'	horizontal effective stress in direction 2
σ_r	radial total stress
σ_r'	radial effective stress
σ_θ	circumferential total stress
σ_θ'	circumferential effective stress
σ_T'	tensile strength under effective strength analysis
$\tau_{r\theta}$	shear stress
ϕ'	friction angle
ϕ_u	friction angle (undrained condition)
A	Skempton's pore pressure coefficient
B	Skempton's pore pressure coefficient
c_u	Cohesion (undrained condition)
C_c	compression index in one dimensional compression
C_r	recompression index in one dimension compression
D	borehole diameter
K_0'	lateral earth pressure coefficient at rest, $K_0' = \sigma_h'/\sigma_v'$
$K_0'^*$	$\sigma_{h1}'/\sigma_{h2}'$
K_{0oc}'	later earth pressure coefficient at rest (overconsolidated)
K_{0nc}'	later earth pressure coefficient at rest (normally consolidated)
LI	liquidity index
OCR	overconsolidated ratio, $OCR = \sigma_{vc}'/\sigma_{v0}'$
P	mud pressure in a borehole or total pressure added around a borehole wall
$P_{S,i}$	mud pressure initiating shear failure
P_T	mud pressure initiating tensile failure
$P_{SC,i}$	mud pressure initiating shear failure at crown (and invert)
$P_{SS,i}$	mud pressure initiating shear failure at springline
P_T	mud pressure initiating shear failure
P_{TC}	mud pressure initiating tensile failure at crown (and invert)
P_{TS}	mud pressure initiating tensile failure at springline
p_c'	preconsolidation mean effective stress
p_0'	initial mean effective stress
R_0	preconsolidation ratio, $R_0 = p_c'/p_0'$
PI	plasticity index
S_u	undrained shear strength
T_u	tensile strength under total strength analysis
u_0	hydrostatic pore pressure
Δu	excess pore pressure

(Luger and Hergarden, 1988), another cavity expansion model (e.g. Vesic, 1972; Yu and Houlsby, 1991 and Yu, 2000), or introduce different constitutive models into solutions of the cavity expansion problem (e.g. Wang and Sterling, 2007 and Buenker, 2015) based on the assumption that $K_0' = 1$. Maximum allowable mud pressure in purely cohesive materials is generally defined as the pressure applied to the inside of the borehole which forces the maximum plastic zone half-way to the ground surface (Van Brussel and Hergarden, 1997), and this approach is accepted by the Pipeline Research Council International (Staheli et al., 1998) and the United States Army Corps of Engineers (USACE) (Carlos et al., 2002). However, the "Delft Equation" and other cavity expansion models may overestimate the maximum allowable mud pressure in saturated clay during Horizontal Directional Drilling, as indicated by Xia and Moore (2006) and Xia (2008).

In this paper, the authors focus on criteria for identifying tensile failure versus shear failure, instead of calculating the maximum allowable mud pressure when drilling in saturated clay. Some use of the new criteria has recently been made by the authors to examine a directional drilling case study (see Lan and Moore, 2016).

2. Theoretical criteria for failure mechanisms

2.1. Elastic solution

Fig. 1 presents the model applied in this paper. Soil in the model is assumed to be homogenous without any stress gradient in the vicinity of the borehole. A linear elastic solution combined with the plane strain condition is employed. Total vertical stress σ_v and total horizontal stress σ_h are usually different. There are four critical points around the borehole (Fig. 1), crown ($\theta = 90°$), springline ($\theta = 0°$and 180°) and invert ($\theta = -90°$). The total radial, shear and circumferential stresses for these critical points in saturated clay have been detailed by Kennedy (2004) as follows:

Crown ($\theta = 90°$) and Invert ($\theta = -90°$):

$$\sigma_r = P \quad (1a)$$

$$\tau_{r\theta} = 0 \quad (1b)$$

$$\sigma_\theta = 3\sigma_h - \sigma_v - P \quad (1c)$$

Springline ($\theta = 0°$):

$$\sigma_r = P \quad (1d)$$

$$\tau_{r\theta} = 0 \quad (1e)$$

$$\sigma_\theta = 3\sigma_v - \sigma_h - P \quad (1f)$$

2.2. Initiation of tensile failure

Fig. 2 shows a relationship between mud pressure P and total circumferential stress σ_θ at the crown. Kennedy (2004) and Kennedy et al. (2004) developed solutions based on a conservative approach where the tensile strength of clay is neglected, so suggest that tensile fracture initiates when total circumferential stress reaches zero. If tensile strength of saturated clay T_u is considered here, tensile fracture will begin when:

$$\sigma_\theta = -T_u \quad (2)$$

So the mud pressure initiating tensile fracture is:

Crown ($\theta = 90°$) and Invert ($\theta = -90°$):

$$P_T = 3\sigma_h - \sigma_v + T_u \quad (3a)$$

Springline ($\theta = 0°$):

$$P_T = 3\sigma_v - \sigma_h + T_u \quad (3b)$$

According to Mitchell and Soga (2005), tensile fracture starts when