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Effects of the hydraulic capacity of advance drainage boreholes on tunnel face stability

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ABSTRACT

Advance drainage improves tunnel face stability by reducing the pore water pressure and thus the destabilizing seepage forces directed towards the tunnel face (Zingg and Anagnostou, 2016). However, the boreholes may become less effective in the presence of casings or where the water inflow volumes are so high that pipe flow develops within the boreholes. Both pipe flow and casings result in water pressure development along the boreholes, thus impeding pore pressure relief in the surrounding ground.

This paper analyses face stability with limit equilibrium computations that take account of the numerically determined hydraulic interaction between the boreholes and the ground. Pipe flow in the boreholes is modelled on the basis of an equivalent hydraulic conductivity model which takes account of the characteristics of the drainage boreholes (roughness, diameter etc.). Casings are considered by modelling the geometry of several slotted or perforated borehole screens. The computational results show that the adverse effects of high-permeability ground, rough borehole walls and sparsely slotted or perforated screens on pore pressure relief may result in significantly greater demand for face support or may even necessitate ground improvement in addition to the advance drainage.

1. Introduction

The stabilizing effects of advance drainage measures in tunnelling are addressed in only a few works, and these assume that atmospheric pressure prevails at the boreholes walls (Zingg and Anagnostou, 2016; Zingg, 2016). This assumption is questionable where the boreholes are cased or the water inflow volumes are large.

Advance drainage boreholes aiming to improve face stability are drilled usually uncased. However, in certain cases even the borehole walls may be unstable and necessitate borehole casings (Fig. 1). Then water passage is limited to the screen openings as the casings are in contact with the borehole wall. Consequently, water pressure develops over a large portion of the borehole walls, impeding pore pressure relief in the surrounding ground and reducing the stabilizing effect of the advance drainage measures.

When tunnelling through a high-permeability ground (such as coarse-grained soft ground or fractured and weathered rocks) deep below the water table, the water inflow volumes may be so large that the flow regime within the drainage boreholes may change from open-channel (free surface) to pipe flow (Fig. 2). As the water within the boreholes is then pressurized, pore pressure in the surrounding ground decreases less than in the case of open-channel flow and, consequently, advance drainage becomes less effective.

To date, these issues have attracted no investigation. To the authors' knowledge only Hong et al. (2007) addressed the question of the hydraulic capacity of drainage boreholes (showing that pipe flow may develop particularly in long boreholes), but only for a specific simplified example and without reference to tunnel face stability.

This paper investigates face stability by considering the hydraulic head field around the tunnel face under pressurized pipe flow conditions or in the presence of casings. The support pressure required for ensuring face stability is determined from the wedge and prism failure mechanism of Anagnostou and Kovári (1996) and exactly as outlined in Section 2 of Zingg and Anagnostou (2016), the only difference being the modelling of the boreholes in the numerical seepage flow analyses.

Inspired by a series of research works on Karst hydrology (*e.g.* Louis, 1967; Atkinson, 1977; Shoemaker et al., 2008a, 2008b) and well and petroleum engineering (*e.g.* Halford, 2000; Birch et al., 2007; Chen et al., 2003), the possibility of pressurized water flow inside the boreholes is taken into account here by considering the borehole interiors as a porous medium with equivalent hydraulic properties. Section 2 derives the equivalent hydraulic conductivity of a borehole by considering turbulent pipe flow, borehole wall roughness and borehole diameter. Afterwards, numerical solutions are presented and a closed-form

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Nomenclature

Latin symbols

a	tunnel radius
c	effective cohesion of the ground
c_w	water compressibility
D	tunnel diameter
d_{dr}	borehole diameter
g	acceleration due to gravity
H	depth of cover
h	hydraulic head
$\bar{h}$	normalized hydraulic head
h_0	initial hydraulic head; depth of tunnel axis below the water table
$\bar{h}_{av}$	average normalized hydraulic head over borehole length
$h_{e,i}$	energy head at point i
$\bar{h}_{max}$	normalized maximum hydraulic head in borehole
h_V	head loss in drainage borehole
H_w	elevation of water table with respect to the tunnel crown
I_x	hydraulic head gradient in drainage borehole
K_g	hydraulic conductivity of the ground
$k_{s,eq}$	equivalent sand roughness of drainage borehole wall
K_x	equivalent hydraulic conductivity in the axial direction
l_{dr}	borehole length
n	number of drainage boreholes
p	pore water pressure
p_0	initial pore water pressure
p_{adm}	admissible average pressure in drainage borehole
p_{atm}	atmospheric pressure
Q	discharge of water, water inflow
q_r	radial specific discharge
q_x	axial flow velocity in the simplified borehole model
$\bar{q}_x$	normalized axial flow velocity
r	radial coordinate
R	size of seepage flow domain
Re	Reynolds number
s	face support pressure
s_{atm}	face support pressure assuming boreholes under atmospheric pressure
s_{nd}	face support pressure in the absence of advance drainage boreholes
$\bar{s}$	drainage effectiveness
v_x	average flow velocity parallel to drainage borehole
x	coordinate parallel to borehole axis
z	geodetic height

Greek symbols

$\alpha_{1,2,3}$	auxiliary variables of the simplified borehole problem
γ'	submerged unit weight of the ground
γ_w	unit weight of water
λ_h	hydraulic friction coefficient
λ_p	coefficient of lateral stress in prism
λ_w	coefficient of lateral stress in wedge
ξ	normalized x-coordinate
υ	kinematic viscosity of water
φ	effective angle of internal friction of the ground
ω	angle between face and inclined slip plane
ω_{cr}	critical angle ω

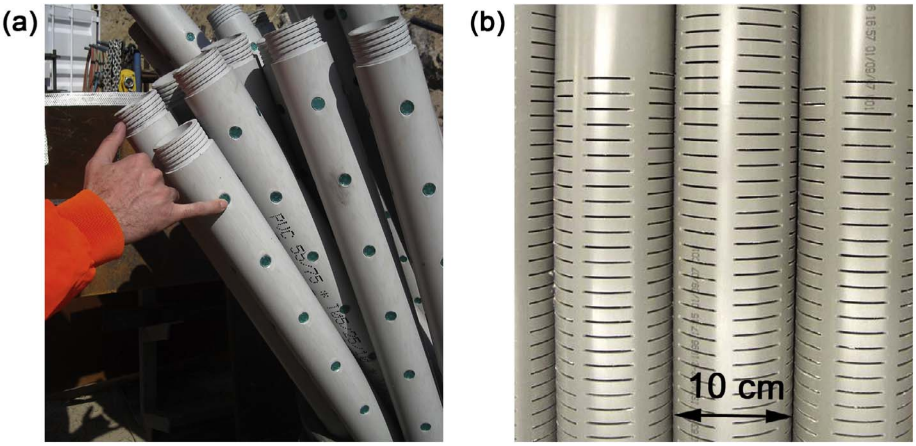

Fig. 1. (a) Perforated screen; (b) slotted screen (courtesy of Baosu Pipe).

solution is derived for the simplest possible problem, the hydraulic interaction between a single borehole and the surrounding ground (Section 3). This problem serves to validate the numerical solutions, identify the significant parameters governing the development of water pressure in the boreholes and illustrate the effects of initial hydraulic head, ground permeability, and borehole diameter as well as wall roughness. Section 4 then presents the computational results for a subaqueous tunnel with a common advance drainage layout consisting of six axial boreholes drilled from the face, and determines factors influencing face stability under high inflow conditions. The validity range of the atmospheric borehole assumption is also given, based on the analytical results (Section 5).

Finally, the impact of casings on advance drainage effectiveness (and thus on face stability) is investigated by modelling the exact casing geometry, considering the screen openings as seepage faces under atmospheric pressure and prescribing a no-flow boundary condition to the casing surface (Section 6). No pipe flow is considered within the boreholes and potential local losses in hydraulic potential due to water entering the openings are neglected (for considerations of local losses at well screens see, for example, Siwoń, 1987; Ouyang et al., 1998; Clemo, 2006). All computations of the present paper assume that the ground is an isotropic porous medium obeying (linear) Darcy's law. The latter presupposes laminar flow conditions, which is a simplifying assumption for highly permeable ground far below the water table. For example during construction of the Lake Mead Intake No. 3 tunnel, a non-linear relationship between slurry pressure p and quantity of water inflow Q was observed at high Q-values (Fig. 3). This non-linearity indicates turbulent seepage flow conditions prevailing in the ground itself (Bear, 1979). The assumption of linear Darcy's law is, however, conservative in the case of highly permeable ground, as it overestimates the specific