Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 191 (2017) 215 – 224
Procedia Engineering
www.elsevier.com/locate/procedia

Symposium of the International Society for Rock Mechanics

Stability Under Seepage Flow Conditions of a Tunnel Face Reinforced by Bolts

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Abstract

We propose a computational method for assessing bolt reinforcement of the tunnel face in cohesive frictional soils and weak rocks under seepage flow conditions. The method is based on limit equilibrium factors and can be applied to reinforcement layouts that are arbitrary in terms of the spacing, length, longitudinal overlapping and installation sequence of the bolts. An investigation is made into the influence of water table height on the stability of a reinforced face. In particular, we show that, if the gradient of the hydraulic head is high, then tensile failure of the ground ahead of the face may be more critical than shear failure. For an approximate hydraulic head distribution in the ground around the tunnel face and assuming uniform face reinforcement, we derive a closed-form solution for the necessary bolting density.

Peer-review under responsibility of the organizing committee of EUROCK 2017

Keywords: Ttunnel face stability; limit equilibrium; face bolts; drained conditions; seepage forces

1. Introduction

Ground reinforcement using bolts is a very efficient measure for stabilizing the face in conventional tunneling. It was applied for the first time in around 1980 in Italian tunnels (*cf.* [1, 2]). Over the years, considerable research has been conducted by numerous authors into the conditions for and the assessment of face stability. A recent review of the state of the art can be found in [3].

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Peer-review under responsibility of the organizing committee of EUROCK 2017
doi:10.1016/j.proeng.2017.05.174

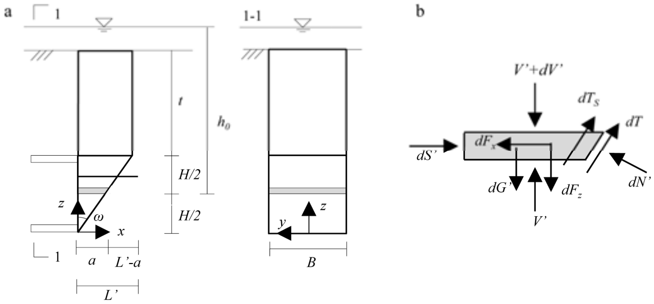

Fig. 1. (a) Failure mechanism and (b) forces acting upon an infinitesimal slice.

Seepage flow may occur in the case of highly permeable ground or very slow excavation and results in hydraulic head gradients in the ground ahead of the excavation face. The hydraulic head gradient acts as a body force, the so-called "seepage force", which is directed towards the face and is therefore unfavorable with respect to its stability.

Although tunneling in water bearing grounds is common in practice and many publications address the stability of the excavation face under such conditions (a recent review can be found in [4]), few studies (*e.g.* [5]) deal specifically with the stability of tunnel faces reinforced by bolts under seepage flow conditions.

The present paper investigates the face stability of a reinforced tunnel face beneath the water table and under drained conditions using the wedge and prism mechanism of Figure 1a and analyses the equilibrium of the wedge based upon the method of slices ([6]).

It extends research works [3] and [7], which used the same approach to investigate the stability of reinforced tunnel faces located above the water table and the stability of tunnel faces in water bearing grounds, respectively, under conditions of uniform support pressure and partial compensation of the hydraulic head at the tunnel face.

Section 2 outlines the seepage-flow analysis and presents a simplified distribution of the hydraulic head, which will be introduced in the limit equilibrium analysis. Section 3 describes the limit equilibrium analysis of the mechanism considered. Section 4 shows some comparative computations.

2. Seepage flow analysis

We determine numerically the three dimensional, steady state hydraulic head field around the tunnel face assuming Darcy's law with uniform ground permeability. The permeability coefficient does not influence the hydraulic head field. A no-flow boundary condition and a constant piezometric head $h_F = 0$ are ascribed to the tunnel wall (impervious lining up to the tunnel face) and to the tunnel face, respectively. At the far-field boundary, the piezometric head is taken equal to the water table elevation h_0. This condition also applies to the water table (no draw-down, i.e. sufficient groundwater recharge from the surface). Figure 2a shows, as an example, a finite element mesh adopted for the calculations, which were performed using the finite element program COMSOL®. A square tunnel cross-section is taken for simplicity (analogously to [9]). The computational domain consists of one half of the system due to the vertical symmetry plane. Figure 3 shows the normalized distributions of the hydraulic head along two characteristic lines (the tunnel axis and the vertical axis z) ahead of the face and above the tunnel, respectively, for an overburden $t = H = B$ and a subaqueous tunnel (water table located above the soil surface, *i.e.* $h_0 > t + 0.5H$), with and without advance drainage (solid and dashed lines, respectively).
The normalized distribution of the hydraulic head depends in general on the normalized overburden t/H ([8]), and on the layout of the advance drainage if any ([4]). The comparative calculations of the following sections consider a tunnel with $t/H = 1$, with and without advance drainage of a specific layout (see caption of Fig. 3).