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Three-dimensional undrained tunnel face stability in clay with a linearly increasing shear strength with depth

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ABSTRACT

The undrained tunnel face stability in clay with a linearly increasing shear strength with depth was investigated by three-dimensional finite element analysis. Three parametric studies were performed to study the effects of the cover depth ratio, overburden stress factor and linear strength gradient ratio on the load factor of the undrained tunnel face stability. The influence of the linear strength gradient ratio on the predicted failure mechanism of the undrained face stability was discussed and examined. An approximate closed-form solution was proposed for three-dimensional undrained tunnel face stability in clays with constant or linearly increasing shear strength profiles with depth.

1. Introduction

Face pressure is the most important parameter that affects soil movements as well as the tunnel face stability during a tunneling process. In practice, the conventional hand calculation of the safety analysis for a tunnel face is based on Broms and Bennermark [3], who defined the stability ratio (N) in Eq. (1).

$$N = (\sigma_s + \gamma H - \sigma_t)/s_u \tag{1}$$

where σ_s = surcharge on the ground surface, σ_t = tunnel face pressure, γ = soil unit weight, s_u = undrained shear strength of clay, C = tunnel cover depth, D = tunnel diameter and H (depth of the tunnel axis) = $C + D/2$. The value of N is then related empirically to the expected deformations, such as $N > 6$: "collapse" and N = 2–4: "elasto-plastic".

Because of its practical importance, a large number of studies on the three-dimensional (3D) undrained face stability of tunnels have been investigated, including the kinematic approach of upper bound (UB) limit analysis using a translational multi-rigid block mechanism [4–6], rotational rigid block failure mechanism [7] and continuous velocity fields [9], 3D finite element limit analysis (FELA) [11], and 3D finite element analysis [16]. Note that the undrained stability of a two-dimensional (2D) plane strain heading (i.e., a simplified version of this 3D problem) was studied by Davis et al. [15] using analytical lower and upper bound limit analysis and by Augarde et al. [1] employing 2D FELA. Currently, 3D stability analyses of the undrained face stability can be performed using numerical analyses (e.g. finite difference or finite element) or a freely distributed MATLAB code (not stand-alone software) called the Tunnel Face Stability Software (TFSS) [8], which represents the most up-to-date of previous studies of Mollon et al. [5–7,9]. However, a simple and accurate design equation of this problem is not available in the literature, while conventional hand calculations of this problem can be performed using Eq. (1) or design charts presented in those cited references. In addition, the previous studies on the 3D face stability of a tunnel have been limited to a homogeneous undrained strength profile, while the effect of a linear strength profile on its stability is poorly understood. Recently, the tunnel face stability in subsoil of Bangkok was examined by Ukritchon et al. [12] using 2D and 3D finite element analysis (FEA).

Note that the 2D plane strain of transverse section of tunnel face stability using unlined circular tunnels in clays were also investigated by FELA, including single tunnel [10,13] and dual circular tunnels [14]. However, such modelling using 2D unlined circular tunnel is not realistic, as compared to the 3D tunnel face stability problem. This is because the tunnel face pressure of the 2D unlined circular tunnel is applied normal to the circumference of the circular tunnel, while that of the 3D case is applied normal to the front face of the tunnel.

In this paper, the 3D undrained tunnel face stability with a linearly increasing strength profile was investigated by 3D FEA. A new equation based on the numerical data of 3D FEA was proposed for

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the reliable and accurate prediction of the safety factor (*FS*) of this problem with homogeneous and linearly increasing shear strength profiles in practice.

2. Method of analysis

The 3D FEA software, PLAXIS 3D Tunnel [2], was employed to investigate the 3D undrained tunnel face stability, as shown in Fig. 1. The numerical model employed only half of the domain due to the problem symmetry. A circular tunnel with diameter (D) was modelled by a cylindrical rigid plate element with a fully rough surface and was assumed to be "wish in place", such that any effect of the tunneling process was neglected. The tunnel had a cover depth (C) measured from the ground surface. The considered soil profile corresponded to a linearly increasing undrained shear strength with depth, where γ is the unit weight of clay, s_{u0} is the undrained shear strength at the ground surface and ρ is the linear strength gradient. The front face of the tunnel was applied by a uniform face pressure (σ_t), while the ground surface was loaded by a uniform surcharge (σ_s). In order to analyze the undrained stability by 3D FEA, the stress-strain behavior of clay was modelled as an elastic-perfectly plastic Tresca material with an associated flow rule, where the undrained Young's modulus (E_u) was $500s_u$, undrained Poisson's ratio (v) was 0.495 and the undrained shear strength (s_u) at a depth (z) was $s_{u0} + \rho z$. The selected E_u/s_u ratio follows a previous stability analysis of a tunnel face using 3D FEA [12], such that there is a very small to no effect of this parameter on the limit load of this stability problem.

The boundary conditions of the symmetrical planes were defined such that only normal displacements of the plane were zero, while the displacements in the other remaining directions were free. Displacements of the bottom planes were fully fixed in all directions, while displacements of the vertical boundary planes were the same conditions as those of symmetrical planes.

Fig. 2 shows an example of the finite element mesh for the 3D undrained stability analyses of a tunnel face. Very fine element distributions were used in all mesh generations, where more elements were discretized in front of the tunnel face in order to obtain an accurate solution. The soil mass was discretized into 15-noded wedge elements with six points of Gaussian integration, while the rigid tunnel lining was discretized into eight-noded quadrilateral elements (four points of Gaussian integration) that are compatible with the soil volume elements.

To simulate the failure of this problem by 3D FEA, the loading multiplier on the surcharge was increased gradually and automatically during each iterative elasto-plastic finite element simulation until the limit state or failure state was reached in the analysis. This state was numerically verified by the convergence of the loading multiplier to a certain value, resulting in a failure surcharge (σ_s).

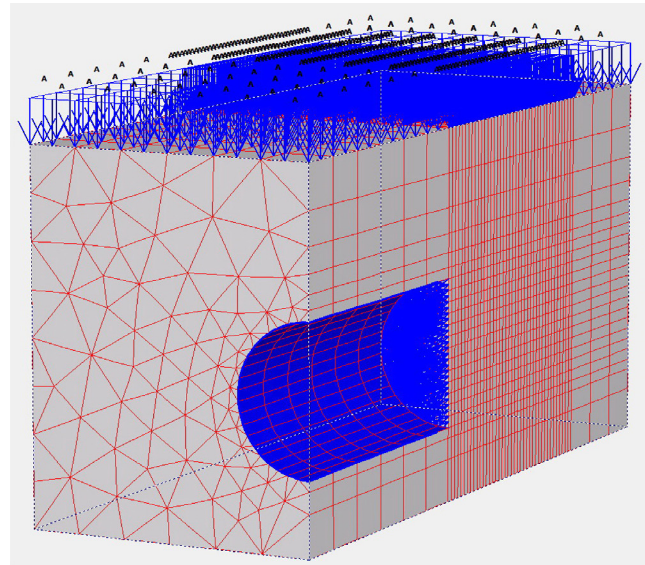

Fig. 2. Example of a finite element mesh used in the 3D FEA.

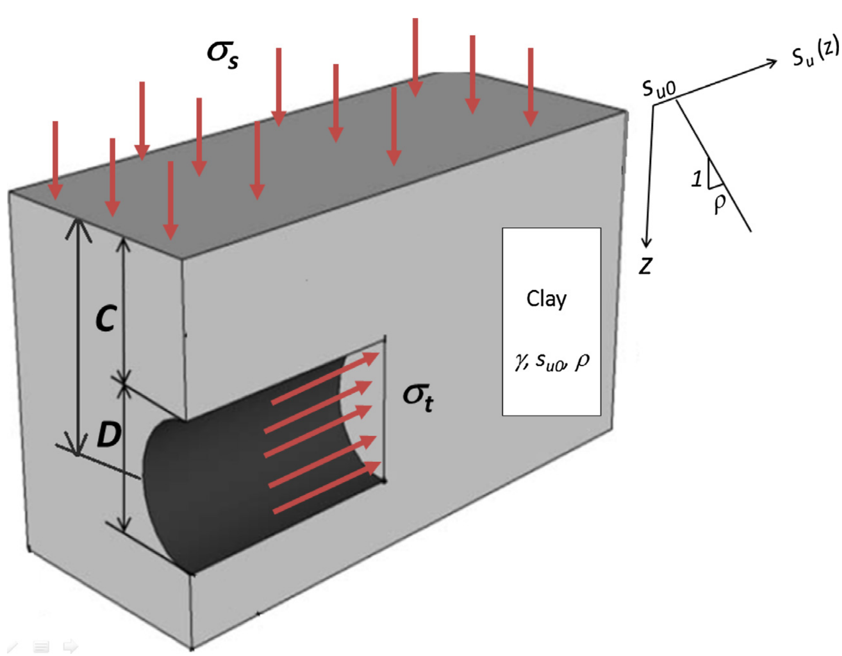

Fig. 1. Problem notation of the 3D undrained tunnel face stability.