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Research Paper

Three-dimensional stability of slurry-supported trenches: End effects

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ABSTRACT

The common procedures for stability analysis of slurry-supported trenches are typically two-dimensional (plane strain), despite the fact that observed failures in the field possess three-dimensional (3D) characteristics. A limit equilibrium (LE) solution for the stability of a slurry-supported trench is presented, where failures are constrained to a finite length. A rotational 3D failure mechanism, derived from variational LE analysis of the slope stability, is adopted and modified to account for the stability of a slurry-supported trench as well as very narrow trenches. The results are presented in the form of stability charts that yield a safety factor for narrow excavation of a given trench. Due to mathematical constraints on the resulting rigid 3D failure geometry, the critical surface of a deep and narrow trench emerges above the toe, termed the shallow failure. Once a shallow failure is initiated, it progressively propagates down to the toe. This above-toe failure mechanism may overestimate the safety of deep excavations in cohesive soils. Consequently, for shallow failures, an alternative approach is introduced to assess the safety of such progressive failures, which ultimately will emerge through the toe. The three-dimensional end effects are investigated to highlight their impact on the stability of a trench, indicating that end effects are most pronounced in purely cohesive soil, diminishing in cohesionless soil. End effects are significant for toe failures in slurry trenches, potentially impacting design.

1. Introduction

Slurry fills are a common form of excavation support and are often economical and safe for diaphragm wall construction. Current design approaches [1–4] apply limit equilibrium (LE) methods as a means of assessing stability. The most common approach of assessing stability [5–7] is based on force equilibrium analysis, considering a simplified wedge failure mechanism and yielding a factor of safety. The LE methods involve idealized, two-dimensional (2D), plane-strain conditions, although trench length is often finite, and the three-dimensional effects can be significant, possibly rendering overly conservative or uneconomical design. For example, Tsai et al. [8] performed a full-scale field experiment on slurry-supported trenches and found that three-dimensional (3D) end effects and soil arching were significant.

In recent decades, there have been several approaches for extrapolating traditional two-dimensional LE methods to 3D conditions. Piaskowski and Kowalewski [9], Washbourne [10] and Fox [4] combined planar or nonplanar ends with a sliding wedge analysis to account for end effects. Based on Terzaghi's arching theory, Huder [11] conducted stability analyses considering both horizontal and vertical stresses in the soil mass surrounding trenches of finite length. Tsai and Chang [12] defined a 3D shell-shaped sliding wedge and then modified Huder's method to calculate the factor of safety for slurry trenches in cohesionless soils. Using a kinematical approach of limit analysis, Han et al. [13] employed a 3D rotational failure mechanism to obtain an upper bound on the safety factor of slurry trenches. Continuum-based approaches, particularly finite element methods [14,15], have also been used to evaluate the stability of slurry trenches in consideration of three-dimensional effects.

Leshchinsky et al. [16] formulated an LE approach for 3D homogenous slope stability and obtained the geometry of the critical 3D slip surface from variational extremization. They demonstrated that their solution is equally valid in the context of rigorous LE and limit analysis (LA) of plasticity, where the upper bound is considered. Because of acceptance in practice, they preferred presentations in the LE framework. Leshchinsky and Baker [17] modified their original rigid-body mechanism to include a

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central cylinder smoothly attached to two end caps, accounting for the 3D end effects on trench stability. Based on the modified 3D rigid-body failure mechanism, Leshchinsky and Mullett [18] produced design charts for vertical cuts and investigated the 3D end effects on the stability of cuts. Ugai and Leshchinsky [19] compared the 3D variational LE results for vertical cuts with 3D results from finite element analyses, demonstrating good agreement between the two different approaches. This study accounts for slurry pressures within an LE framework, exploring the end effects on the stability of slurry trenches. A set of design charts are presented for application in preliminary design.

2. Formulation and 3D mechanism

2.1. Definition of the problem

Fig. 1 shows the notation and conventions used in formulating the stability analysis of slurry-supported trenches. A trench is excavated to a depth of H in homogeneous soil and filled with a slurry H_s high from the bottom. The groundwater table is located at a depth of D_w. The unit weights of soil, slurry and water are γ, γ_s and γ_w, respectively. The soil is assumed to be rigid, obeying the Mohr–Coulomb failure criterion. Thus, the average mobilized shear strength along a potential slip surface is

$$\tau = [c' + (\sigma - u)\tan\phi']/F_s = c_m + (\sigma - u)\tan\phi_m \quad (1)$$

where c' and ϕ' are the effective cohesion and effective internal angle of friction, respectively; c_m ($c_m = c'/F_s$) and ϕ_m ($\tan\phi_m = \tan\phi'/F_s$) are the mobilized cohesion and mobilized friction angle, respectively; σ is the total normal stress along a potential slip surface; u is the pore water pressure along a potential slip surface; and F_s is the factor of safety. For short-term stability, the undrained shear strength (c_u) can be applied, and the mobilized shear strength is then $\tau = c_u/F_s = c_m$.

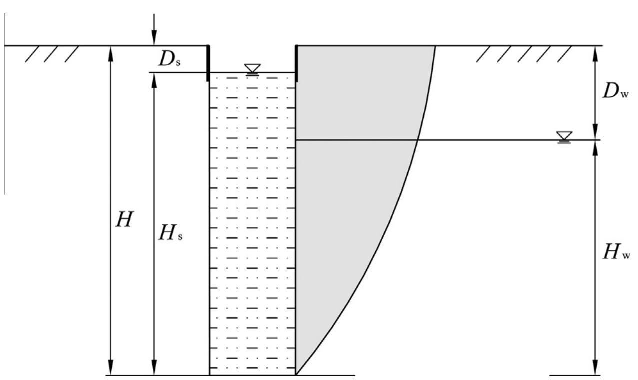

Fig. 1. Notation and convention.

In formulating the problem, the following assumptions are made:

(1) The soil is homogeneous and isotropic.
(2) The sliding soil mass moves intact as a rigid body.
(3) Additional shear strength due to matric suction above the groundwater table is not considered.
(4) No permeation of slurry into the native soil is considered.
(5) Tension cracks are not considered.
(6) No surcharge is applied at the ground surface.

2.2. 3D failure mechanism

The 3D failure mechanism proposed by Leshchinsky et al. [16] is a result of the variational minimization of a safety factor functional. Based on the application of standard variational techniques (Euler's equations) seeking the most critical slip surface geometry in homogeneous slopes, Leshchinsky et al. [16] obtained the differential equation for the 3D slip surface as

$$\frac{d\rho}{d\beta} = -\psi_m \sin\sqrt{\rho^2 + \left(\frac{d\rho}{d\alpha}\right)^2} \quad (2)$$

where $\rho = \rho(\alpha, \beta)$ is the slip surface in spherical coordinates (ρ, α, β), as shown in Fig. 2. The centre of this spherical system is located at an unknown point (x_c, y_c, z_c) (to be determined numerically), and the mobilized friction is denoted as $\psi_m = \tan(\phi_m) = \tan(\phi')/F_s$.

Eq. (2) has two fundamental solutions for the potential slip surface geometry, as illustrated in Fig. 3. However, because the variational formulation assumed univalued functions (i.e., each point x, y has only one value of z), the resulting surfaces in Fig. 3 are restricted in their potential existence. The univalued mathematical constraint implied that no overhanging cliffs are physically considered in the LE (or LA) analysis of rigid body rotation.

Following the introduction of the basic two slip surface geometries, Leshchinsky and Baker [17] presented a third, more general surface, which is a smooth combination (in space) of the two basic solutions as

$$\rho = A\exp(-\psi_m\beta)\sin\alpha \quad \text{for } |y| \geqslant l_c \quad (3a)$$

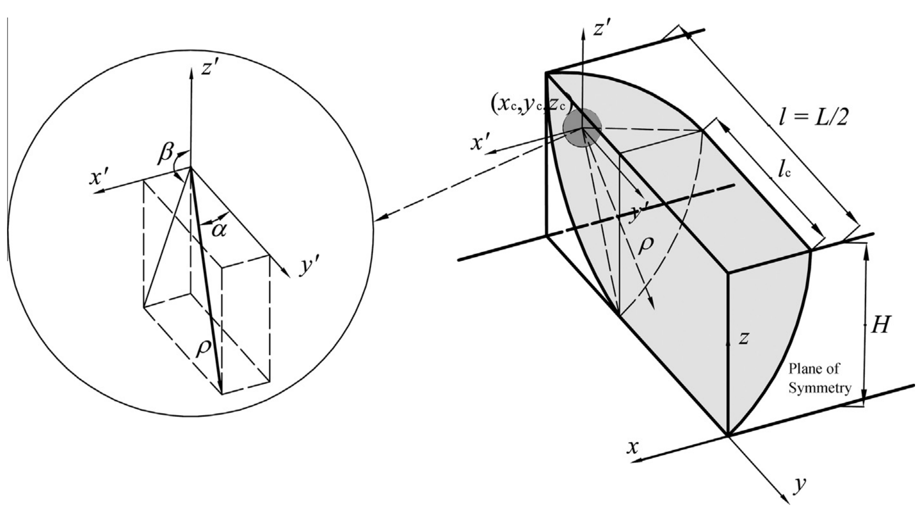

Fig. 2. The failure surface and the coordinate system for a symmetrical structure.