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Research Paper

Undrained stability of a single circular tunnel in spatially variable soil subjected to surcharge loading

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ABSTRACT

The stability of tunnels is an important problem in geotechnical engineering. Most of the previous studies dealing with the stability of unlined tunnels are deterministic in nature and do not consider the soil spatial variability. This study investigates the influence of spatial variability on the undrained stability of an unlined circular tunnel, using Random Adaptive Finite Element Limit Analysis (RAFELA). The effect of spatial variability is investigated for tunnels having two different ratios of $\gamma D/c_u$, for different spatial correlation lengths and tunnel depths. The results indicate that the effect of spatial variability depends on $\gamma D/c_u$ and the depth of the tunnel.

1. Introduction

Ensuring the stability of a tunnel during the construction process requires considerable attention from an engineering standpoint, as a collapse could have significant consequences. With rapid urbanisation, more tunnels are being constructed in highly congested and densely populated areas. Not surprisingly, the stability of tunnels is a subject which has received a lot of attention in the literature. The studies of Assadi and Sloan [3], Sloan and Assadi [26] and Sloan and Assadi [27] were amongst the first to address this issue using Finite Element Limit Analysis (FELA), considering undrained soil and plane-strain conditions. To date, a number of studies have been performed where the effects of shape (circular [e.g. 16,27], square [e.g. 3,17,26], rectangular [1], tall [34]), soil type (purely cohesive and cohesive-frictional soils, [e.g. 3,17]), spacing [e.g. 35,36,38,39], and strength non-homogeneity [e.g. 11,26,33] on tunnel stability were investigated using numerical limit analysis. These studies address the stability of tunnels subjected to surcharge loading and self-weight and provide useful guidelines on the loads that would trigger collapse, but they are all purely deterministic. Work by Griffiths et al. [7] and Griffiths and Fenton [8] indicates that the response of a structure can be significantly affected by the spatial variability of the surrounding soil mass. Although some studies have been performed on the effect of spatial variability on tunnel face stability [4,5,22,23,32] and ground movements [28–30], no previous research has been devoted to the stability of unlined tunnels in spatially variable soil. The present work, therefore, aims to investigate the stability of a single circular unlined tunnel in spatially variable undrained soil subjected to surcharge loading using numerical limit analysis and random fields.

Finite Element Limit Analysis (FELA) uses efficient methods for computing the collapse load in a direct manner, without tracing the complete load-displacement path. The lower and upper bound FELA methods developed at the University of Newcastle were first established by Sloan [24] and Sloan [25], respectively, and were applied to problems of tunnel stability by Sloan and Assadi [3,26,27]. Since then a number of studies, as described in the previous paragraph, have employed FELA for assessing the stability of tunnels, utilising more efficient solvers. Recently, FELA with adaptive remeshing has been combined with random fields to tackle stability problems where the soil materials vary spatially [2]. This combination, also known as RAFELA (Random Adaptive Finite Element Limit Analysis), utilises efficient adaptive meshing techniques to achieve tight bounds on the collapse loads of geostructures in random soils. This paper employs RAFELA for investigating the effect of spatial variability on the undrained stability of unlined tunnels.

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List of symbols

$\mathbf{A}$	equilibrium matrix	α	load multiplier
D	diameter of tunnel	γ	unit weight of soil
c_u	undrained soil shear strength	θ	actual spatial correlation length (in units of length)
e	error estimate	$\mathbf{\Theta}$	dimensionless spatial correlation length
f	yield function	μ_{c_u}	mean value of undrained shear strength
FS	Factor of Safety	$\mu_{N_{ran}}$	mean of the random stability number
H	depth of the tunnel	v_{c_u}	coefficient of variation in the undrained shear strength
N_{det}	deterministic stability number	$\sigma_{N_{ran}}$	standard deviation in the random stability number
N_{ran}	random stability number	ρ	correlation function
n_{sim}	number of Monte-Carlo simulations	σ_t	internal/stabilising pressure
$\mathbf{p_0}$	constant part of the external load	σ_s	surcharge load
$\mathbf{p}$	optimised load	$\boldsymbol{\sigma}$	vector of stresses
p_f	probability of failure		

2. Methodology

2.1. Geometry

The numerical model considered in the present work is shown in Fig. 1. A tunnel of diameter D and depth H is studied with no internal pressure σ_t (that would help resist collapse or cause a blowout). The soil is modelled as a Tresca material having undrained cohesion c_u and unit weight γ. The soil domain has a width of at least $9D$ and a depth of at least $7D$ for $H \leqslant 3D$, and was increased for larger depths to minimise boundary effects. The bottom boundary is fixed while the vertical boundaries are fixed only in the horizontal direction. A continuous loading is applied to the surface of the domain, with smooth interface conditions, in order to determine the surcharge load σ_s.

2.2. Adaptive Finite Element Limit Analysis

Limit analysis is a powerful tool for evaluating the stability of geostructures. Based on the bounding theorems of classical plasticity, it considers the soil to be perfectly plastic and follows an associated flow rule. According to the lower bound theorem, any statically admissible stress field will yield a lower bound estimate on the true collapse load. A stress field is considered statically admissible if it satisfies the equilibrium equations, the stress boundary conditions, and the yield conditions (i.e. the stresses lie

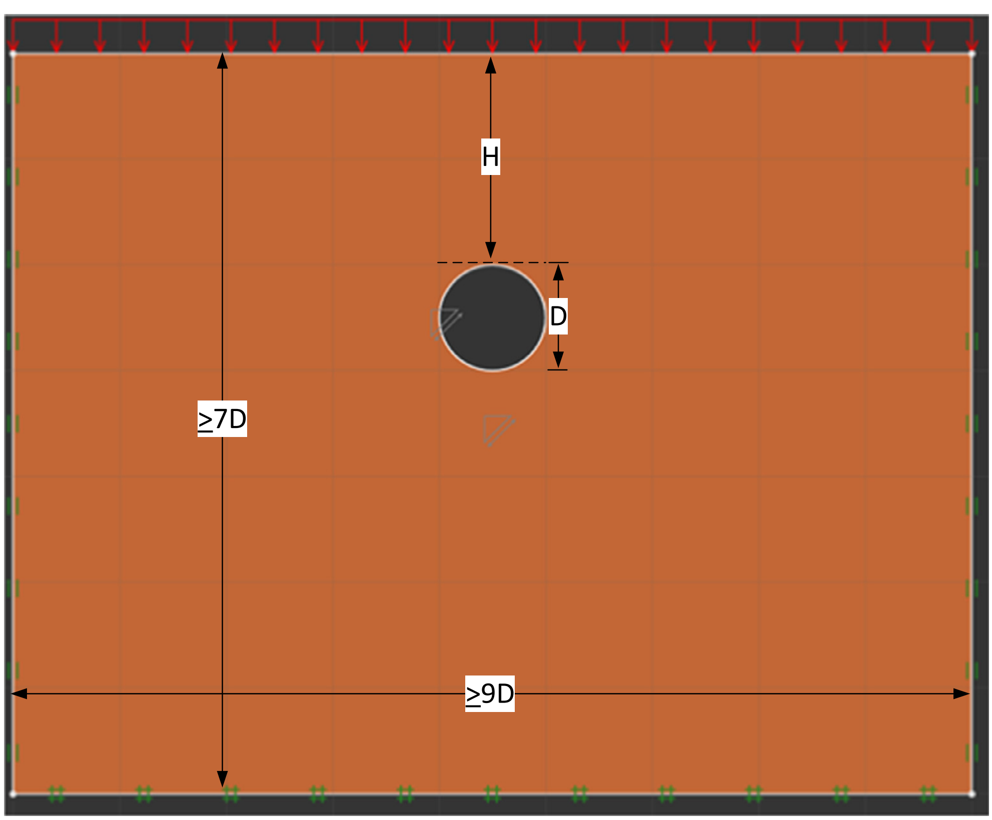

Fig. 1. Tunnel geometry.