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Eulerian finite element model for stability analysis of circular tunnels in undrained clay

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ABSTRACT

Traditional Lagrangian finite element (FE) method may encounter numerical problems due to severe element distortion in the analysis of tunnel stability, which requires the simulation of large deformation and post-failure behaviour of soil. To overcome these limitations, this paper presents an Eulerian FE model, developed to evaluate the stability of circular tunnels in undrained clay. An application example was first presented in detail to illustrate both the approaches and principles for the simulation. Then parametric analyses of tunnel stability using the Eulerian FE method were performed to verify the validity of the developed model. The computed limit support pressures showed good agreements with the solutions from the finite element limit analysis, demonstrating that it is applicable in the stability analysis of a circular tunnel. Meanwhile, Lagrangian FE analysis was also performed for a comparison of performance with the developed Eulerian FE model. The computed results by Lagrangian FE models were shown significantly overestimating the stability of the circular tunnels, which was found to be caused by the decrease of tunnel diameter during the analysis. The Eulerian FE method developed in this paper can inherently avoid this problem, highlighting its advantage in the stability analysis of circular tunnels.

1. Introduction

Knowledge of stability conditions for tunnels is crucial to mitigate the risk of damage to existing nearby structures. A rational estimation of the minimum support pressure that stabilise the soil around the tunnel helps prevent excessive ground deformations and hence is of practical use.

Experimental studies have been carried out to analyse the stability of both unlined cavities [1,2] and tunnel headings [3,4]. However, as the tests were performed under controlled laboratory conditions, the conclusions drawn from them were mainly used as qualitative references in practice.

For more practical use, analytical or semi-analytical methods have been developed to assess tunnel stability, which included both limit equilibrium methods [5,6] and limit analysis methods [7–10]. Although analytical approaches are favoured by engineers for their simplicity, they often make light account of the soil deformation behaviour, which seems a significant deficiency [11].

In this regard, finite element (FE) method may be an effective tool in the analysis of tunnel stability [12–14], which can take the stress-strain relation of soils into account and thus predict more realistic soil behaviour. However, as the tunnel stability problem usually involves large deformation and post-failure response of soil, traditional FE method (Lagrangian scheme) may suffer the disadvantage of severe element distortions and hence lose accuracy.

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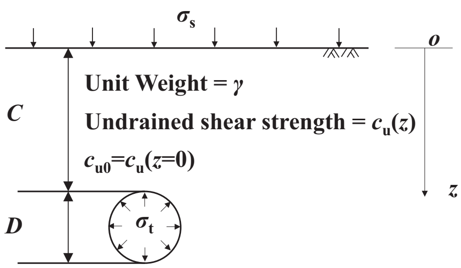

Fig. 1. Stability problem of a plane strain circular tunnel.

To achieve such computational purpose, the discrete element method (DEM), as a feasible alternative, has been adopted to simulate the process of tunnel collapse [15,16]. Being proposed based on non-continuum mechanics, this approach, which defines material property via interparticle contacts, is suitable for modelling the behaviour of granular soils (e.g. sands). However, as for cohesive soils (e.g. clays), because the effects of pore water can hardly be reflected by the contact behaviour of particles, some macroscopic characteristics under undrained conditions, e.g., incompressibility, cannot be realistically simulated.

The Eulerian FE method [17,18] is a promising approach well suited to solve numerical problems associated with large deformation, which has been successfully used in the studies of a few geotechnical problems, such as penetration of spudcan foundations [19,20] and progressive failure of clay slopes [21]. Because it is proposed under the classical framework of continuum mechanics (similar to traditional Lagrangian FE method), it is quite suitable for the simulating the behaviour of clays. In this article, as an extension of this technique, the authors established an Eulerian FE model to evaluate the stability of a circular tunnel in undrained clay. To facilitate its application, an example was provided with both the approaches and principles for the simulation presented in detail. The accuracy of the model was demonstrated by carrying out parametric analyses and comparing their results with the solutions from finite element limit analysis, which showed its good applicability and reliability in the analysis of the tunnel stability.

2. Problem description

The stability of a three-dimensional tunnel was usually simplified as a plane strain problem in cross section, which gives conservative solutions and hence is useful in practice [10]. This article, as an initial exploration in Eulerian FE analysis of the tunnel stability problem, mainly focuses on the idealised case of a plane strain circular tunnel. A schematic of the problem can be seen in Fig. 1.

The circular tunnel has a diameter of D and a cover depth of C. The soil has a unit weight of γ and an undrained shear strength of $c_u(z)$, which may vary with depth z. The ground surface is subjected to a surcharge of σ_s, and the tunnel circumference, free to move, is supported by an internal pressure of σ_t. The stability of the circular tunnel can be assessed by a parameter N denoted as $(\sigma_s\text{-}\sigma_t)/c_{u0}$, which is often adopted in the analyses of stability problems.

3. Simulation approaches

3.1. Deformation of soil in Eulerian framework

The simulations were implemented in the commercial software package ABAQUS™ (Version 2016). In the Eulerian framework, nodes are fixed in space, and material flows through elements that do not deform. Therefore, the main task of an Eulerian analysis is to track the Eulerian material as it flows through the fixed mesh. In ABAQUS/EXPLICIT, this is implemented by computing a parameter, i.e., the Eulerian volume fraction (EVF), which represents the proportion of material that fills an Eulerian element. If the Eulerian element is full of a material, EVF = 1; if no material is present in the element, EVF = 0.

3.1.1. Eulerian algorithm

In each time increment, the Eulerian algorithm comprise two phrases: a traditional Lagrangian phase and a transport phrase.

As shown in Fig. 2, the Lagrangian phrase is firstly performed. During this phrase, the nodes are temporarily fixed within the material so that the elements can slightly deform with the material.

During the following phrase, the transport phrase, deformation is suspended and the elements are automatically remeshed, and the corresponding material flow between neighbouring elements can be known via computing EVF.

3.1.2. Eulerian material advection

As material flows through the Eulerian mesh, the state variables are transferred between elements by advection: first, the state variables, e.g., mass, energy, stresses and other field quantities are set constant in each old mesh; then the value of the variables is integrated over the new mesh after remeshing; the new value of the variable is determined via dividing the value of each integral by the volume of the material.