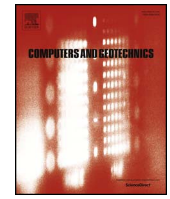
Computers and Geotechnics 96 (2018) 246–257

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo



Research Paper

Bearing capacity analysis of a saturated non-uniform soil slope with discretization-based kinematic analysis

Changbing Qin*, Siau Chen Chian

Department of Civil & Environmental Engineering, National University of Singapore, Singapore 117576, Singapore

ARTICLE INFO

Keywords:
Pore water effect
Discretization-based kinematic analysis
Conventional upper bound analysis
Ultimate bearing capacity
Saturated soil slope

ABSTRACT

In contrast to conventional kinematic analysis postulating a log-spiral failure mechanism, this study adopts a discretization technique to generate a kinematically admissible failure mechanism, using the forward difference method. A vertical infinitesimal trapezoidal element, similar to that in slices method of limit equilibrium, is chosen so as to consider pore water effect within slopes. The work rate-based balance equation yields the optimal kinematic solution of limiting surcharge near the crest of the slope. The bearing capacity of a saturated non-uniform slope is sought through optimization and verified with conventional kinematic analysis.

1. Introduction

Slopes with high pore water pressure are more susceptible to failure. Such instability cases are principally induced by the following two reasons: (1) increase in ground water table leading to a reduction in effective stresses; and (2) increase in bulk unit weight due to presence of water which acts as a destabilizing force.

A commonly adopted approach in slope stability is the limit analysis method in which the failure load can be narrowed to a range composed by a lower and upper bound. Unlike the limit equilibrium method, the plasticity theory tends to produce more meaningful solutions considering the constitutive relationship of soils. The lower bound limit analysis of a wedge slope was investigated with block element method, with the factor of safety optimized in a nonlinear sequential quadratic programming algorithm [1]. In the case of ultimate bearing capacity state, it is of much interest to engineers to estimate the ultimate slope failure using the upper bound theorem, without consideration of stress components. As elaborated in Chen [2], the upper bound theory dictates that if a kinematically admissible velocity field can be established, then the actual collapse load is either lower than or equal to the external load determined from the equilibrium of the external and internal rates of work. Many researchers [3–10] applied this method to estimate stability problems in geotechnical engineering with upper bound solutions of stability factor and/or safety factor. However, in these studies, the closed-form solutions were derived from a pre-assumed failure mechanism which is only appropriate for a homogeneous soil.

In the application of upper bound theorem, the adoption of a log-spiral curve to characterize the velocity discontinuous surface is a sound estimate of the potential slip surface, which is substantiated by Chen and Liu [11]. The principle is related to the associated flow rule based on which the velocity vector is always inclined at an angle of friction with respect to the tangential line of a point along the sliding surface. Based on this rule, a novel approach was proposed by Mollon et al. [12–14] to generate a potential collapse mechanism through 'point-to-point' method. This spatial discretization technique was initially used in stability analysis of a pressurized tunnel face, and the results are proved to be in good agreement with field measurements. More importantly, this technique enables the generation of a discretized collapse mechanism and allows the consideration of variation of strength parameters in non-uniform soils with ease, which can be found in Qin and Chian [15].

In this present study, a novel procedure for predicting the stability of a saturated non-uniform slope is introduced. A discretized failure mechanism is generated using the discretization technique. The kinematic analysis is thereafter executed based on the discretized elements where the total external work rates and internal energy dissipation are obtained through summation. Finally, the upper bound solution can be derived in closed form in terms of limiting surcharge acting on the ground surface at the crest.

2. Methodology

2.1. Pore water effect in upper bound theorem

In the application of the kinematic approach, rigid block assumption is usually made for simplification. The geomaterials should be perfectly plastic and comply with the associated flow rule. Alternatively, non-

* Corresponding author.
E-mail address: changbingqin@u.nus.edu (C. Qin).

https://doi.org/10.1016/j.compgeo.2017.11.003
Received 11 July 2017; Received in revised form 2 October 2017; Accepted 8 November 2017
Available online 22 November 2017
0266-352X/

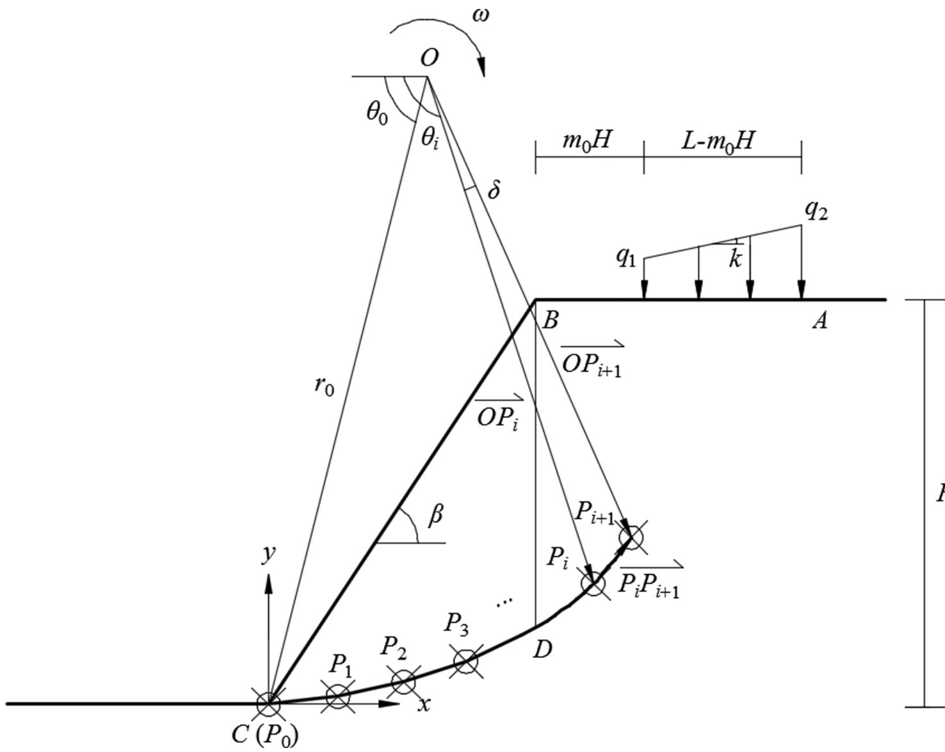


Fig. 1. Generation of a potential failure surface using the forward difference 'point-to-point' method.

associated flow rule can be accounted for by introducing a dilatancy angle. Volumetric strain can be incorporated in 3D analyses. The upper bound theorem is mainly used to resolve three classical issues in geotechnical engineering: (1) slope stability problems [3–10], (2) earth pressure calculations [11,16] and (3) ultimate bearing capacity of foundations [17,18].

In the presence of water effect, the conventional kinematic approach is performed based on effective stress analysis for Mohr-Coulomb material so as to directly quantify the inter-particle contact forces. Pore water effect is regarded as an external loading exerted on the soil skeleton and the boundary. In existing theoretical literatures, the pore water pressure is introduced by a scalar parameter, r_u, for the case of fully saturated soils.

As interpreted in Viratjandr and Michalowski [19], when considering the water effect on slope stability, both the seepage force and the buoyancy force should be accounted for, and the corresponding work rate can be explicitly expressed through summation of work rates of pore pressure on soil skeleton and the boundary, namely,

$$\dot{W}_u = -\gamma_w \int_V \frac{\partial h}{\partial x_i} v_i dV + \gamma_w \int_V \frac{\partial Z}{\partial x_i} v_i dV = -\int_V u\dot{\varepsilon}_{ii} dV - \int_S u n_i v_i dS \tag{1}$$

where is the unit weight of water, h denotes the hydraulic head for defining the seepage force $-\gamma_w \partial h/\partial x_i$, Z refers to the elevation head for definition of the buoyancy force $\gamma_w \partial Z/\partial x_i$, $\dot{\varepsilon}_{ii}$ is the volumetric strain rate defined as $\dot{\varepsilon}_{ii} = \partial v_i/\partial x_i$, u denotes the pore water pressure, V corresponds to the volume of potential failure block, S is the surface bounding the volume V, and n_i is the outward unit vector normal to the surface S.

In order to incorporate the water effect in the upper bound theorem, Eq. (1) should be added to the side of total external work rate, i.e.,

$$\int_V \sigma_{ij}\dot{\varepsilon}_{ij} dV \geqslant \int_S T_i v_i dS + \int_V X_i v_i dV - \int_V u\dot{\varepsilon}_{ii} dV - \int_S u n_i v_i dS \tag{2}$$

Eq. (2) is the complete form of upper bound theorem under the pore water effect. When the equality condition is satisfied under a kinematically admissible velocity field, the optimal upper bound solution is determined under the ultimate limit state. The following kinematic analysis is executed based on this principle.

2.2. Discretization technique

In the application of upper bound analysis, a kinematically admissible collapse mechanism is necessitated for calculation of internal and external work rates. The extent of slope failure block is affected by soil properties and geometrical features of slopes. Conventionally, the critical state of slope failure is estimated considering a pre-postulated collapse mechanism. In this case, the accuracy is highly influenced by the appropriateness of the failure mechanism. Common forms of failure mechanism include the translational block, rotational failure or a combination of these. Note that, for $c-\varphi$ materials in a homogeneous soil stratum, the log-spiral failure mechanism is a sound approximation of the physical failure. However, it is hardly able to consider non-uniform soil properties using the conventional upper bound analysis. In an effort to overcome this shortcoming, the discretization technique is adopted as described below.

The contour of the potential slip surface of a 2D discretized collapse mechanism is systematically generated using the preceding known point on the contour of the mechanism. Following that, the final slip surface is gradually formed 'point-by-point' (i.e. discretization) in a given coordinate system. During the discretization procedure, the kinematical admissibility condition, also termed as normality condition, requires the slip surface to meet the velocity vector at the angle of internal friction of the soil. The discretized collapse mechanism aids to account for different values of friction angle in layered soil strata.

In slope engineering, it is not uncommon to observe toe failure, particularly in steep slopes and soils with high friction angles, which will be analyzed herein. In such cases, the slip surface commences at the slope toe (Point C), as the origin of the coordinate system, and terminates at the ground surface at the crest, as shown in Fig. 1. In order to account for the change in pore water pressure at different locations in the soil strata, the velocity discontinuous lines can be formed by the same discretization procedure. The assumptions in this study are: (1) the geomaterials should be $c-\varphi$ material which follows an associated flow rule; (2) the soil slope is fully saturated with no water flow; (3) a toe failure is considered herein; (4) the potential failure blocks rotate as a rigid body around the same rotation center O with the same angular velocity.