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Effect of Material Model on the FEM Based Stability Analysis of Slope

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Abstract

Due to rapid development of computer technology, Finite element method (FEM) has gained increasing popularity over traditional methods in geotechnical engineering. FEM based numerical analysis for geotechnical engineering problems such as the stability analysis of slope requires the incorporation of any material model. In this paper, different material models such as the Mohr-Coulomb, Modified Mohr-Coulomb, and Drucker-Prager models are used to numerically investigate their effects on the computation of the factor of safety with water and without water. A model slope is considered and the material properties are assigned. FEM based software GEO5 is used to calculate the factor of safety. From the analysis, it is found that Modified Mohr-Coulomb model yields higher factor of safety compared to that of Mohr-Coulomb model and Drucker-Prager mode while Mohr-Coulomb material model yields the lowest factor of safety. Incorporation of water lowers the factor of safety of slopes regardless of the material model as expected. Material models appear to have insignificant effect on the evolution pattern of the equivalent plastic strain.

Keywords: Material model, FEM, Slope stability, Factor of safety.

1. Introduction

Slope, made of soil, is often observed in different engineering structures such as the road and railway pavements, dams, etc. The proper design of slope is important for the stability of such engineering structures. The accurate approximation of the factor of safety of the slopes often requires the adaption of the precise methods. Conventional methods such as Bishop [1], Fellenius [2], Morgenstern-Price [3], Spencer [4] and Janbu [5] are often used due to the ease in calculation. Consequently, many research works have been reported in the literature that considered the conventional limit equilibrium methods [6-8]. However, these methods have several limitations. It requires many prior assumptions. Moreover, only simple models can be considered by using the limit equilibrium method. With the tremendous advances of computational power, the numerical approach such as the finite element method (FEM) has been implemented in the stability analysis of slope [9-10]. The important point of FEM based stability analysis is that it requires no prior assumption. The failure surface of slope is not predetermined or pre-set in FEM. Moreover, any complex shape of slope can easily be considered and complex multi-material slopes can be analyzed using FEM. The FEM based model analysis of slope requires the incorporation of any material model. In this paper, the effect of different material models on the factor of safety of slope by FEM is studied using GEO5 [11] with water and without water. Mohr-Coulomb material model, Modified Mohr-Coulomb material model and Drucker-Prager material model are used in this study. The consequences of using different models in the FEM based study have been investigated and the numerical results have been reported.

2. Finite element method in slope stability analysis

Finite element method (FEM) is a very widely used and powerful tool for solving boundary value problems. It is used for appropriate solution of boundary value problems in stress analysis, fluid flow, heat transfer etc. In FEM, the actual continuum is divided into small and regular subdivisions referred to as finite elements which are interconnected at specified joints referred to as nodes. The solution is approximated over each finite element and the governing equations for each finite element are assembled to analyze the behavior of the externally loaded structures through the boundary. The stability of slopes are traditionally solved by the conventional limit equilibrium method. But, limit equilibrium method is limited by assumptions regarding the analysis method itself. By contrast, the most difficult part of the use of FEM in slope stability analysis is the calculation of factor of safety. Such difficulties can be overcome by the introduction of the strength reduction technique proposed by

Zienkiewicz et al. [12]. Griffiths, and Lane [9] also used FEM for the calculation of the factor of safety by following the strength reduction technique.

3. Geometry of the numerical model

The geometry of the numerical model considered in the present study is depicted in Fig. 1. All the dimensions in the model are given in meter. In the numerical model, a slope angle of 45° is used. The geometric boundaries are horizontally constrained on the left and right sides and completely fixed at the bottom of the geometry. The geometric model is incorporated in GEO5 [11] and the material properties are assigned. The desired material model is selected and the whole geometry is divided into small subdomains known as mesh for FEM based analysis. In this study, only triangular shape mesh is generated. After generation of mesh and assigning related properties, the stability analysis is performed by strength reduction methods [9]. The generated mesh (size=0.5 m) within the boundary of the numerical model is depicted in Fig. 2.

4. Material properties

In the present study, a single material (homogeneous soil) is used, the properties of which are shown in Table 1. The properties of material are selected with the aid of the previous studies from the literature. This is done because the aim of present study is to focus the importance and the effect of the material model in the calculation of the factor of safety of a numerical model slope and not a real slope.

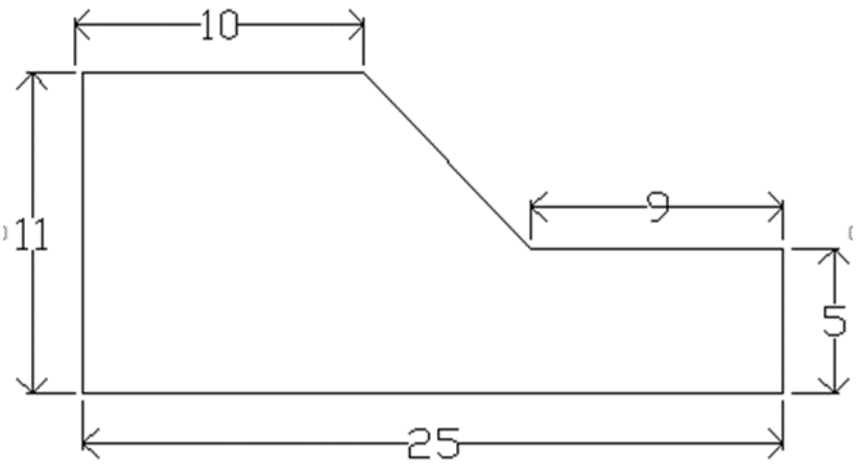

Fig. 1. Geometry of the numerical model of slope considered in the present study

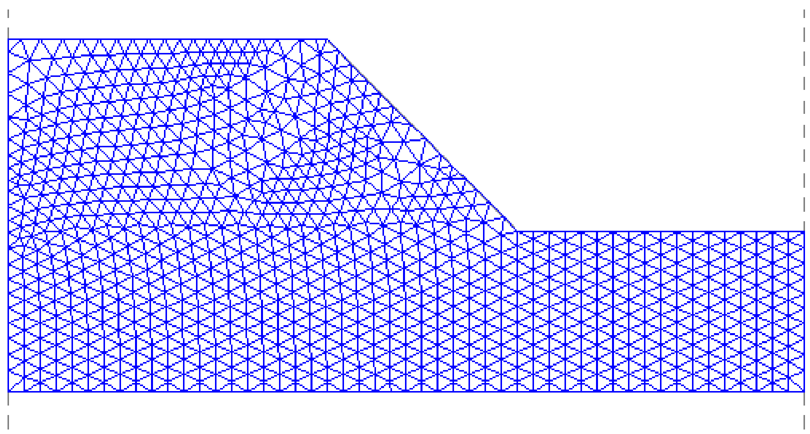

Fig. 2. Model slope with mesh (mesh size=0.5 m) without considering any water

Table 1. Material properties used in the present study

Material (soil) parameters	Value
Cohesion, c (kN/m²)	10
Frictional angel, ϕ (deg)	20
Unit weight, γ (kN/m³)	18
Modulus of elasticity, E (MN/m²)	8
Poisson's ratio, ν	0.3
Dilation angle, ψ (deg)	0.0

5. Effect of material models in slope stability analysis

In the present FEM based analysis, three different material models are considered. They are: Mohr-Coulomb material model, Modified Mohr-Coulomb material model and Drucker-Prager material mode. Three material models are varied to find the factor of safety for different element numbers and mesh sizes. In the following sections the effect of different material models on the stability analysis of slopes are reported.

Mohr-Coulomb Model

The FEM analysis using Mohr-Coulomb material model requires parameters such as modulus of elasticity, poison's ratio, angle of internal friction and cohesion. The latter two parameters serve to define the yield condition. The angle of dilation must also be specified. The failure surface of Mohr-Coulomb model can be expressed as follows:

$$\tau = \sigma \tan \phi + c \tag{1}$$

where, τ represents the shear stress, σ represents the normal stress, ϕ represents the angle of internal friction (slope of the failure envelope) and c represents the cohesion (the intercept of the failure envelope with the τ axis). The Mohr-Coulomb yield surface is represented as a non-uniform hexagonal cone in the principal stress space.

The factor of safety considering Mohr-Coulomb material model with 6-node triangle element for eight different mesh configurations is presented in Table 2. The analysis is carried out with water and without any water. Note that the factor of safety varies up to an approximate element number of 2300 (mesh size 0.5 m) for this material model considering the water and without considering the water. Beyond that, the factor of safety remains almost constant even though the size of mesh decreases and the number of element increases.

Modified Mohr-Coulomb Model

The Modified Mohr-Coulomb model unlike the Mohr-Coulomb model smoothes out the corners of the Mohr-Coulomb yield surface. A slightly stiffer response of the material can be expected with the Modified Mohr-Coulomb plasticity model when compared to the Mohr-Coulomb and Drucker-Prager models [11]. The factor of safety using the Modified Mohr-Coulomb material model for 6-node triangle element for eight different mesh configurations considering water and without considering water is shown in Table 3. Note that the factor of safety varies up to an approximate element number of 2300 (mesh size 0.5 m) for this material model. Beyond that, the factor of safety remains almost constant even though the size of mesh decreases and the number of element increases. It is noted that Modified Mohr-Coulomb material model yields elevated factor of safety compared to Mohr-Coulomb model.

Drucker-Prager Model

Drucker-Prager yield surface is smooth and appears as a cylindrical cone in the principal stress space. The Drucker-Prager model modifies the Mohr-Coulomb yield function to avoid singularities associated with corners [11]. The Drucker-Prager yield criterion [13] can be given by

$$f = \sqrt{J}_2 - \alpha I_1 - k = 0 \tag{2}$$

where, J_2 is the second invariant of the deviatoric stress tensor, I_1 is the first invariant of the stress tensor, α and k are the material constants determined from the experiments.

The factor of safety using the Drucker-Prager material model for 6-node triangle element for eight different mesh configurations considering water and without considering water is shown in Table 4. Note that the factor of safety varies up to an approximate element number of 2300 (mesh size 0.5 m) for this material model with water and without water. Beyond that, the factor of safety remains almost constant even though the size of mesh decreases and the number of element increases. It is noted that Drucker-Prager material model yields a bit higher factor of safety compared to Mohr-Coulomb model but less than the Modified Mohr-Coulomb model whether water is used or not.

Table 2. Factor of safety for Mohr coulomb material model

Mesh size (m)	Elements	Factor of safety without water	Factor of safety with water
1	703	1.25	1.23
0.9	834	1.23	1.21
0.8	996	1.23	1.21
0.7	1256	1.23	1.20
0.6	1662	1.21	1.20
0.5	2291	1.20	1.17
0.4	3407	1.20	1.17

Table 3. Factor of safety for Modified Mohr Coulomb material model

Mesh size (m)	Elements	Factor of safety without water	Factor of safety with water
1.0	703	1.42	1.41
0.9	834	1.41	1.39
0.8	996	1.42	1.39
0.7	1256	1.41	1.41
0.6	1662	1.41	1.37
0.5	2291	1.39	1.37
0.4	3407	1.37	1.35

Table 4. Factor of safety for Drucker-Prager material model

Mesh size (m)	Elements	Factor of safety without water	Factor of safety with water
1.0	703	1.33	1.32
0.9	834	1.32	1.30
0.8	996	1.33	1.30
0.7	1256	1.33	1.30
0.6	1662	1.32	1.28
0.5	2291	1.30	1.27
0.4	3407	1.28	1.27

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6. Effect of material models on the contour of equivalent plastic strain

The effect of the material model on the contour of the equivalent plastic strain for dry sample (without any water) is depicted in Fig. 3. The red color indicates the maximum equivalent plastic strain while the green color indicates the minimum equivalent plastic strain. Note that, the highest equivalent plastic strain is observed near the slope. Note also that the material model appears to have minimum effect on the evolution of the equivalent plastic strain.

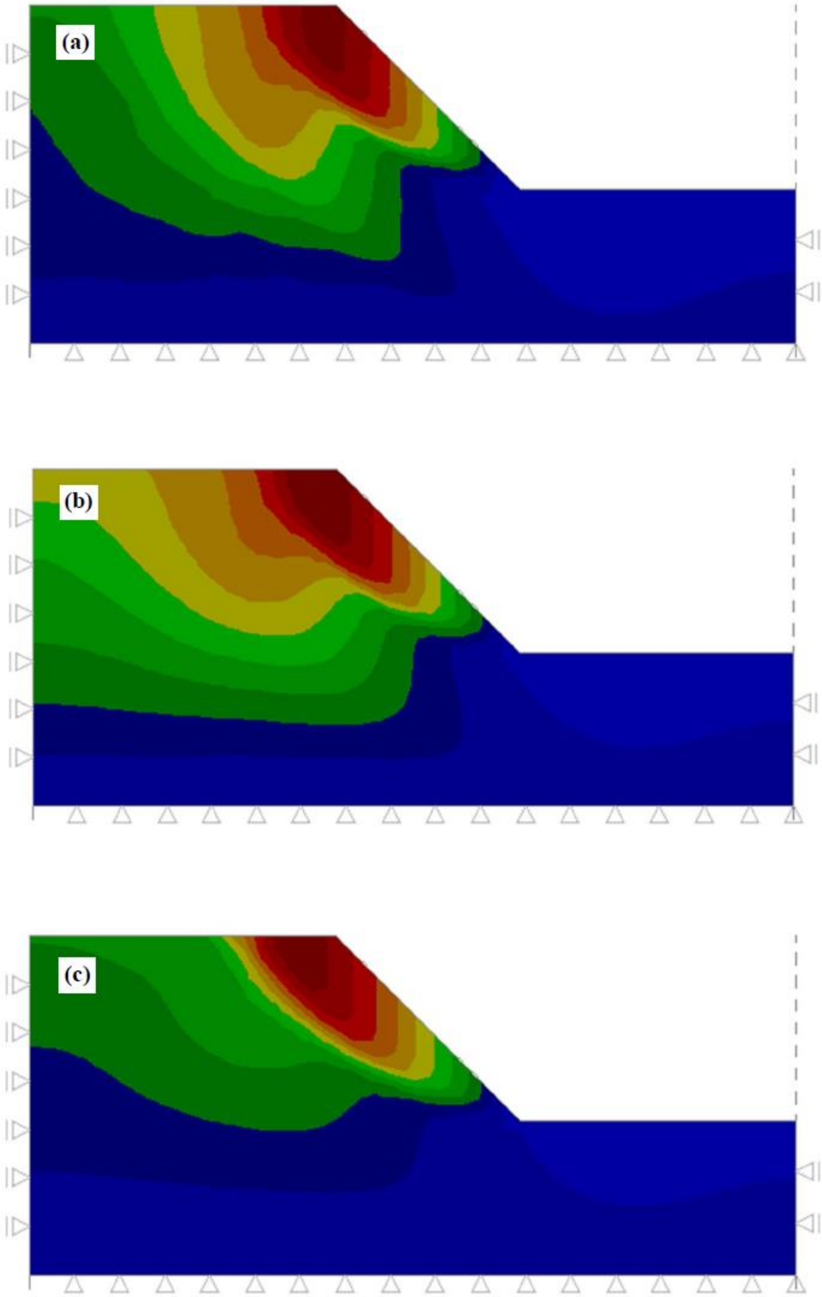

Fig. 3. Contour of the equivalent plastic strain for mesh size 0.5 m without considering water: (a) Mohr-Coulomb Model; (b) Modified Mohr-Coulomb Model; (c) Drucker-Prager Model

7. Conclusions

The effect of the material model on the FEM based stability analysis of slope has been investigated considering water and without considering water. Different material models such as the Mohr-coulomb, Modified Mohr-Coulomb and Drucker-Prager models are used to investigate their effects on the computation of the factor of safety. Some of the important points of the study are summarized as follows:

(i) Modified Mohr-Coulomb model yields higher factor of safety compared to that of Mohr-Coulomb and Drucker-Prager models. Mohr-Coulomb material model yields the lowest factor of safety.
(ii) Incorporation of water lowers the factor of safety of slopes regardless of the material model.
(iii) Material models appear to have negligible effect on the evolution pattern of the equivalent plastic strain.

8. References

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