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Deformation and failure mechanism of slope in three dimensions

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ABSTRACT

Understanding three-dimensional (3D) slope deformation and failure mechanism and corresponding stability analyses are crucially important issues in geotechnical engineering. In this paper, the mechanisms of progressive failure with thrust-type and pull-type landslides are described in detail. It is considered that the post-failure stress state and the pre-peak stress state may occur at different regions of a landslide body with deformation development, and a critical stress state element (or the soil slice block) exists between the post-failure stress state and the pre-peak stress state regions. In this regard, two sorts of failure modes are suggested for the thrust-type and three sorts for pull-type landslides, based on the characteristics of shear stress and strain (or tensile stress and strain). Accordingly, a new joint constitutive model (JCM) is proposed based on the current stability analytical theories, and it can be used to describe the mechanical behaviors of geo-materials with softening properties. Five methods, i.e. CSRM (comprehensive sliding resistance method), MTM (main thrust method), CDM (comprehensive displacement method), SDM (surplus displacement method), and MPM (main pull method), for slope stability calculation are proposed. The S-shaped curve of monitored displacement vs. time is presented for different points on the sliding surface during progressive failure process of landslide, and the relationship between the displacement of different points on the sliding surface and height of landslide body is regarded as the parabolic curve. The comparisons between the predicted and observed load–displacement and displacement–time relations of the points on the sliding surface are conducted. The classification of stable/unstable displacement–time curves is proposed. The definition of the main sliding direction of a landslide is also suggested in such a way that the failure body of landslide (simplified as "collapse body") is only involved in the main sliding direction, and the strike and the dip are the same as the collapse body. The rake angle is taken as the direction of the sum of sliding forces or the sum of displacements in collapse body, in which the main slip direction is dependent on progressive deformation. The reason of non-convergence with finite element method (FEM) in calculating the stability of slope is also numerically analyzed, in which a new method considering the slip surface associated with the boundary condition is proposed. It is known that the boundary condition of sliding surface can be described by perfect elasto-plastic model (PEPM) and JCM, and that the stress and strain of a landslide can be described properly with the JCM.

1. Introduction

Stability analysis of slope has attracted a great attention for a very long period of time, and great achievements have been made. Some numerical analytical methods are proposed, e.g. the ordinary method, the simplified Bishop method, the Janbu method, the Fellenius method, the Morgenstern method, the strength reduction method (SRM) of finite element method (FEM) for slope stability analysis.

The limit equilibrium method using rigid block is widely used in engineering. With the development of numerical analysis and computer capability, many researchers try to improve various calculation methods for slope stability analyses, for instances, the three-dimensional (3D) regular limit equilibrium equations (Liu et al., 2007; Zhu and Qian, 2007; Li and Qian, 2010; Guo et al., 2011) in which six equilibrium conditions are satisfied. In their study, the whole sliding body was concerned and the stresses of sliding surface were corrected (Zheng, 2000, 2007; Yao et al., 2001; Liu et al., 2002; Yin et al., 2002; Wang, 2004; Zhang et al., 2005; Lu et al., 2010; Zheng et al., 2013) by using an algebraic eigenvalue to solve the problem of non-convergence numerical calculation of the 3D regular limit equilibrium equations.

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The above-mentioned methods for slope stability analysis are basically based on the critical stress state (or the limit equilibrium state). The critical stress state refers to the possible failure of slope occurring along the entire slip surface where a critical state is reached simultaneously, thus the critical stress state is considered to be a peak-stress state. The fundamental properties of the thrust-type and pull-type landslides are studied, and it is commonly acknowledged that the post-failure stress states are located in the posterior or front region and the pre-peak stress state is situated at the front or posterior part of landslide for the thrust-type and pull-type landslide, respectively. Only one point (for two-dimensional, 2D) or one curve (for 3D) is under the critical stress state. In this regard, this point or curve is defined as the “critical stress state”, which changes from the non-failure state to failure state with progressive deformation. Actually, the failure of landslide takes place progressively, e.g. some zones are under the post-failure stress state, local zone under the critical stress state, and the others under the pre-peak stress state. It can be noted that large deformation occurs in the post-failure stress state, and small deformation is observed in the zone of pre-peak stress state of landslide. In view of landslide deformation, the mechanical parameters at the peak stress state for entire sliding surface have no physical meanings (except the critical stress state), even for the isotopic and homogeneous landslide. The mechanical parameters at the critical stress state can only describe the behaviors of a point (for 2D case) or of a curve (for 3D case) of the sliding surface, suggesting that the above-mentioned methods describing the stability factor are in a sense only the empirical methods for landslide (Lu et al., 2007, 2008, 2012, 2013, 2014).

In this paper, two failure modes are proposed for the thrust-type landslide, i.e. type I (failure occurs basically along the weak layer) and type II (failure happens in the posterior region along the weak layer and in the front region along the landslide body); whilst three failure modes are suggested for the pull-type landslide, i.e. type I (the shear failure occurs along the weak layer merely), type II (the shear failure happens in the front region along the weak layer and in the posterior part along the landslide body), and type III (the shear failure occurs in the front region along the weak layer and the pull failure happens in the sliding mass). These failure modes are controlled by shearing behaviors of soft interlayer or by shearing and pulling properties of slip body. For the thrust-type landslide, the critical stress state point (or curve) moves gradually from the posterior to the front region, and for the pull-type landslide, it transfers from the front region to the posterior. In other words, the landslide failure will continue to induce the new critical stress state and the post-failure state. The whole process curve between load (T) and displacement (S) is also divided into types I, II and III, based on which the stability along the sliding surface is divided into stable, less stable and unstable regions, respectively. A new joint constitutive model (JCM) is suggested which can describe the mechanical behaviors of types I and III, and its mechanical parameters can be calibrated accordingly. The relationships between displacement (S) of monitoring points on sliding surface and time (t) are employed for thrust-type and pull-type landslides. The S-shaped curve is suggested to describe the relation between S and t of the monitoring points on the sliding surface. Different S-shaped curves are presented for separated points on the sliding surface at a time. The relationship between S and t is classified into two types, i.e. type I (steady displacement–time curve) and type II (unsteady displacement–time curve). This classification is related to the mechanical properties of the whole process between load and displacement. The characteristic of the parabolic curve exists between displacement of different points on the sliding surface and height of landslide body, which varies with deformations and can be used to predict the landslide failure. The stability factors obtained by the traditional calculating methods are compared under different stress states. The maximum stability factor occurs under the critical stress state and the minimum under the residual stress state if the same method is employed. Its value varies from the maximum to the minimum, dependent on the stress states in which the sliding surface is located, i.e. the critical stress state, post-failure stress state or residual stress state. Basically, several methods are suggested to evaluate the stability of landslide, for instance, the comprehensive sliding resistance method (CSRM), main thrust method (MTM), comprehensive displacement method (CDM), surplus displacement method (SDM), and main pull method (MPM). The SRM is usually employed by the FEM, but it is not suitable for comparing the obtained stress and strain fields with those in field when the strength reduction coefficient (F) is not equal to 1. The cause of non-convergence in SRM analysis can be attributed to the different deformation values among the sliding body, varying stiffness of sliding surface and sliding bed, different strength reduction, and large deformation in local region. A new method, sliding surface boundary method (SFBM), is proposed associated with FEM. A perfect elasto-plastic model (PEPM) or JCM can be used to describe the mechanical behaviors of the sliding surface. It is proven that the PEPM cannot well describe the progressive failure process of landslide, except the residual stress state; whilst it is possible for the JCM to describe the mechanical behaviors of the whole process of the progressive failure of landslide body. It is shown that the main slip direction is only dependent on the failure body of landslide (simplified as collapse body), the strike and the dip are the same as the collapse body. The rake angle is taken as the direction of vector sum of sliding force or of displacement of collapse body, i.e. the main slip direction is variable with deformation development.

2. Deformation mechanism, failure modes and control standards

2.1. Thrust-type landslide

The equations for deformation and force equilibrium of landslide body are established based on the fundamental mechanical behaviors of geo-materials. For the thrust-type landslide, it is assumed that the posterior region is under the post-failure stress state, and the front region is situated at the pre-peak stress state. The critical stress state is located in the region between the post-failure stress state and the pre-peak stress state, meaning a point (2D case) or a curve (3D case), when the sliding force is equal to the sliding resistance along the sliding surface direction. Two points, P^{resid} and P_{c}, are situated at the post-failure stress state, one point P^{peak} (for 2D case) is at the critical stress state, and other points, P_{b}, P^{yield} and P_{a}, are at the pre-peak stress state (see Fig. 1a and d). The mechanical behaviors of these points are associated with different stress states (the post-failure stress state, the pre-peak stress state, and the peak stress state) of the whole load–displacement curve (see Fig. 1d). The relationship between displacement of monitoring points on the sliding surface and time is shown in Fig. 1a and b. A steady curve is presented for the points P^{yield} and P_{a} because their stress state is within the yield limit stress space, but an unsteady curve is observed for the points P^{resid}, P_{c}, P^{peak} and P_{b}, which are located in the post-failure stress state and the space between the yield limit stress and the peak stress. It can be noted that the mechanical properties of soft interlayer (sliding surface) are very important for controlling the stability of landslide (see Fig. 1d).

The displacement–time curve can be roughly defined as the “S-shaped curve” for slope, which can be also divided into stable (types I and III) and unstable curves (type II) as shown in Fig. 2. The displacement–height curve of sliding surface is a parabolic one at