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Pseudo-static stability analysis of rock slopes reinforced by passive bolts using the generalized Hoek–Brown criterion

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ABSTRACT

The stability analysis of passive bolt-reinforced rock slopes under seismic loads is investigated within the framework of the kinematic approach of limit analysis theory. A pseudo-static method is adopted to account for the inertial forces induced in the rock mass by seismic events. The strength properties of the rock material are described by a modified Hoek–Brown strength criterion, whereas the passive bolts are modeled as bar-like inclusions that exhibit only resistance to tensile-compressive forces. Taking advantage of the ability to compute closed-form expressions for the support functions associated with the modified Hoek–Brown strength criterion, a rotational failure mechanism is implemented to derive rigorous lower bound estimates for the amount of reinforcement strength to prevent slope failure. The approach is then applied to investigating the effects of relevant geometry, strength and loading parameters in light of a preliminary parametric study. The accuracy of the approach is assessed by comparison of the lower bound estimates with finite element limit analysis solutions, thus emphasizing the ability of the approach to properly predict the stability conditions and to capture the essential features of deformation localization pattern. Finally, the extension of the approach to account for slipping at the interface between reinforcements and surrounding rock mass is outlined.

1. Introduction

Rock slope stability analysis still remains an important problem in rock engineering and many contributions have been made to address this issue (e.g. Zhang and Chen, 1987; Drescher and Christopoulos, 1988; Michalowski, 1995; Yu et al., 1998). From an engineering viewpoint, several methods and techniques have been developed in the last decades with the purpose to improve stability of slopes. Among the most attractive reinforcement techniques, one may quote the technique of soil nailing and rock bolting. In this respect, inserting passive fully grouted bolts leads to a net improvement of the overall strength of rock mass, which in turn results in an increase in slope stability. Both experimental and theoretical analyses were performed in order to assess the efficiency of such kind of slope reinforcement.

On one hand, several works based on laboratory tests have been performed to study the stability of nailed soil slopes (Hong et al., 2005; Giri and Sengupta, 2009, 2010; Rawat et al., 2014). Shaking table tests were performed to examine the dynamic behavior of nailed slopes (e.g. Hong et al., 2005; Giri and Sengupta, 2009, 2010). Centrifuge model tests of nailed soil slopes were also conducted under several loading conditions (e.g. Tei et al., 1998; Zhang et al., 2013, 2014). Parametric studies were performed in these works to optimize the efficiency of slope nailing, and field experiments were also conducted with the aim of assessing the same problem (e.g. Zhou et al., 2009; Guo and Hamada, 2012; Blanco-Fernandez et al., 2013). The experimental results clarified the effects of several parameters on the stability of nailed slopes.

On the other hand, several theoretical and numerical methods were developed to study the stability of reinforced slopes by nails or bolts. They could be roughly categorized into five groups: limit equilibrium (Patra and Basudhar, 2005; Wei and Cheng, 2010a; Maleki and Mahyar, 2012; Wei et al., 2012), elastoplastic finite element (FE) (Sharma and Pande, 1988; Zhu and Zhang, 1998; Zhu et al., 2003; Maleki and Mahyar, 2012; Kim et al., 2013; Kato et al., 2014; Sahoo et al., 2015) or finite difference approaches (Wei and

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Cheng, 2010a, b; Halabian et al., 2012; Wei et al., 2012; Cheuk et al., 2013; Lin et al., 2013; Wang et al., 2015), yield design or limit analysis (de Buhan, 1986; Juran et al., 1990; de Buhan et al., 1989; Michalowski, 1997, 1998a, b; Ausilio et al., 2000; Porbaha et al., 2000; Siad, 2001; He et al., 2012; Clarke et al., 2013), and other theoretical/numerical methods (e.g. Kim et al., 1997; Koyama et al., 2012; Seo et al., 2014) such as the discrete element method (Kim et al., 1997).

Referring to the theoretical framework of limit analysis and related lower and upper bound theorems, the stability of reinforced slopes has been investigated considering gravitational forces (Michalowski, 1997, 1998a; Porbaha et al., 2000; Siad, 2001) or gravitational forces combined with seismic acceleration (Michalowski, 1998b; Ausilio et al., 2000; He et al., 2012). In most of these works, the strength capacities of the constitutive geomaterial were described by the Mohr–Coulomb failure criterion. However, it was experimentally proved that the strength envelopes of rocks are nonlinear (Hoek and Brown, 1980, 1997; Hoek, 1983; Agar et al., 1987; Goodman, 1989; Marinos and Hoek, 2001; Jiang et al., 2003). Among the nonlinear failure criteria proposed in the literature, the Hoek–Brown failure criterion appears well suitable for describing the strength resistance of rocks. In this context, recent studies implemented the latter failure criterion to assess the stability of rock slopes (Collins et al., 1988; Sonmez et al., 1998; Yang et al., 2004a, b; Serrano et al., 2005; Yang and Zou, 2006; Yang, 2007; Li et al., 2008, 2009, 2012; Zheng et al., 2009; Saada et al., 2012), while equivalent Mohr–Coulomb parameters were evaluated from the Hoek–Brown failure criterion to investigate the stability of rock slope reinforced by bolts by means of the finite difference code FLAC3D (Wang et al., 2015).

Sonmez et al. (1998) developed a practical procedure for back determination of shear strength parameters mobilized in closely jointed rock slopes that obeys the Hoek–Brown failure criterion. The same nonlinear failure criterion was used by Zheng et al. (2009) in order to search the critical slip surface of a slope based on the strength reduction technique. Collins et al. (1988) evaluated the stability of homogeneous rock slopes with the original Hoek–Brown failure criterion. Serrano et al. (2005) conducted a theoretical analysis of the stability of infinite rock slopes with different hypotheses of simplified seepage flow nets. They used the original and modified Hoek–Brown failure criteria. The important effect of groundwater flow in the slope was underlined. Yang et al. (2004a, b) investigated the stability of rock slopes whose strength properties were described by a modified Hoek–Brown failure criterion. Yang et al. (2004b) considered a rock slope subjected only to its weight, and compared their results to previous results provided by Collins et al. (1988) for the original Hoek–Brown failure criterion. In addition, Yang et al. (2004a) considered a rock slope subjected to seismic loads. The upper bound theorem of limit analysis was applied to the seismic and static stability problems of homogeneous rock slope with the modified Hoek–Brown failure criterion. This approach enabled the authors to evaluate a least upper bound of the safety factor of the slope. Besides, the seismic displacement of rock slopes with nonlinear Hoek–Brown failure criterion was studied by Yang (2007). More recently, Li et al. (2008, 2009) improved the results provided by Yang et al. (2004a, b). These authors derived FE upper and lower bound solutions in order to provide stability charts for rock slopes. Within the same context, Li et al. (2012) performed reliability assessments for rock slopes based on the Hoek–Brown failure criterion. They used a new form of safety factor for rock slope design and presented its use in probabilistic assessment.

This paper focuses on the face stability analysis of rock slopes reinforced by passive bolts, considering that the rock strength properties could be modeled by means of a modified Hoek–Brown failure criterion. The analysis proposed herein for the rock slope stability under the combined loading defined by gravitational and earthquake-induced forces is based on the implementation of the kinematic approach of limit analysis. The analysis relies upon the pseudo-static method, thus implicitly assuming that dynamic effects of earthquake motions on the variations of rock strength properties are disregarded. In addition, only the horizontal pseudo-static force during an earthquake sequence is accounted for. Indeed, Chen and Liu (1990) reported that the effects due to the vertical component of seismic forces are generally negligible. However, when the horizontal seismic acceleration becomes relatively large (compared to gravitational forces for instance), this effect should be included in design analysis. The effects of seepage forces are not considered in the present analysis. The principle of how these driving forces could be accounted for in the stability analysis can be found in Saada et al. (2012).

It should be noted that within the assumption above-mentioned, the main objective of the paper is to assess lower bound estimates for the so-called “required reinforcement strength” defining the reinforcement ratio that is required for preventing failure. The methodology implemented in the subsequent analysis follows from the upper bound theorem based on the kinematic approach of limit analysis.

2. Statement of the problem and method of analysis

This section provides a description of the geometry of the problem together with the loading mode and the strength properties of the reinforced rock material. The general framework of kinematic approach of limit analysis is also briefly presented.

2.1. Geometry and loading mode

The plane strain stability analysis considered herein refers to a homogeneous and isotropic rock slope reinforced by a series of passive bolts. The slope is defined by the angle β (inclination with respect to the horizontal plane) and height H, as shown in Fig. 1. Referring to the coordinate system (x_1, x_2, x_3) associated with the orthonormal frame (T, $\underline{e}_1$, $\underline{e}_2$, $\underline{e}_3$), where the origin T is located on the top of the slope, the stability analysis shall be addressed within the formulation of a two-dimensional (2D) plane strain problem parallel to x_1-x_2 plane.

Regarding the loading mode, the material system is basically submitted to gravitational forces as well as inertial forces developed in the rock mass by the passage of seismic waves. In the present simplified analysis, the acceleration distribution within the rock mass is accounted for through the concept of average seismic coefficient (Seed, 1979). In addition, only the horizontal component of earthquake acceleration will be considered in the analysis, and it is assumed that the horizontal distribution of acceleration is uniform within the rock mass. Denoting by γ the rock unit weight, the

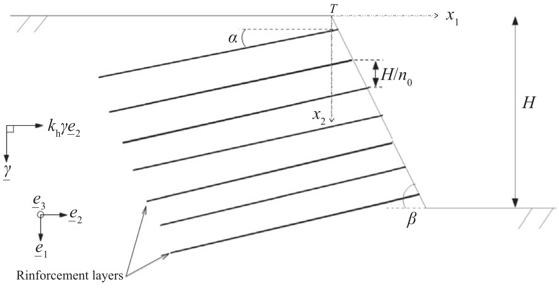

Fig. 1. Geometry and loading mode of studied rock slope.