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Soils and Foundations 57 (2017) 237–251

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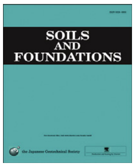

Effect of the vertical earthquake component on permanent seismic displacement of soil slopes based on the nonlinear Mohr–Coulomb failure criterion

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Received 18 December 2015; received in revised form 1 November 2016; accepted 23 December 2016
Available online 13 April 2017

Abstract

In the present study, a model is developed to calculate the upper bound of the seismic displacement of a slope based on the sliding rigid block model. In this model, it is assumed that the geotechnical materials satisfy the nonlinear Mohr–Coulomb (M–C) failure criterion, and the instantaneous shear strength parameters are introduced by the "external tangent method". A sequential quadratic program, based on the nonlinear iteration procedure, is also employed to obtain the optimal solution for the objective function. Using the upper bound method and the Newmark sliding rigid block model, the effect of the vertical earthquake component on the permanent displacement of slopes is studied under the following two conditions: (1) It is assumed that the vertical acceleration is in phase with the horizontal acceleration; (2) Actual vertical ground motion records are used (i.e., the vertical and horizontal accelerations are mutually independent). The results show that the nonlinear parameter m significantly affects the permanent displacement of slopes, and that the effect of the vertical earthquake component on permanent displacement cannot be ignored. The impact of the vertical earthquake component on slope stability will be overestimated if the vertical acceleration is in phase with the horizontal acceleration.

Keywords: Seismic slope; Permanent displacement; Vertical earthquake; Nonlinear failure criterion; Sliding rigid block model; Upper bound limit analysis

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1. Introduction

There are at least four major indices, including the factor of safety, the permanent displacement, the yield seismic coefficient, and the shape of the slip surface, for evaluating slope stability under the action of an earthquake. Several methods, such as the limit equilibrant method, limit analysis, the shear beam method, and the finite element method, can be used to solve seismic slope stability analysis problems. The seismic displacement of slopes can quantify the slope damage and provide a reliable basis for determining slope stability. Newmark (1965) presented a method for estimating seismic-induced sliding movement by adopting the rigid-plastic sliding block model proposed by Ambraseys (1959) and recommended the use of slope sliding movement instead of the factor of safety for evaluating the seismic slope performance. As revealed by Marcuson (1994), and recently reported by Reitherman (2010) and Garini et al. (2011), Newmark's method was inspired by an earlier unpublished work by R. V. Whitman related to a study on the displacements of the Panama Canal slopes. Many researchers have expanded on these studies by

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Peer review under responsibility of The Japanese Geotechnical Society.

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http://dx.doi.org/10.1016/j.sandf.2016.12.002
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discussing the seismic displacement of slopes based on geotechnical experiments and actual earthquake damage data with the Newmark block model (Chang et al., 1984; Ling and Leshchinsky, 1995; Cai and Bathurst, 1996; You and Michalowski, 1999; Michalowski and You, 2000; Zhang et al., 2013).

A large quantity of spectrum records have shown that the vertical peak acceleration of the area around the epicenter is often high (Kavazanjian, 1995; Parise and Jibson, 2000; Nouria et al., 2008; Leschinsky et al., 2009); this may influence the stability of slopes significantly. The effect of the vertical earthquake component on the stability of geotechnical structures (e.g., slopes and embankments) has been investigated by many scholars (Ling et al., 1997; Huang et al., 1997; Liu et al., 2005; Ingles et al., 2006; Sawicki et al., 2007; Zhang et al., 2013, 2014, 2015). In terms of the problem of whether or not the vertical ground motion plays an important role in the dynamic stability of slopes, there are various inconsistencies in the obtained results. A few studies have indicated that the effect of the vertical acceleration can be ignored (Huang et al., 1997; Zhang et al., 2015), while other studies have suggested that the vertical acceleration significantly affects the seismic performance and the permanent displacement of slopes when the horizontal acceleration is high and the slope is steep (Ling et al., 1997; Ling and Leshchinsky, 1998; Ingles et al., 2006). Although the vertical seismic force is considered, the methods for investigating its effect on slope stability vary. Ling and Leshchinsky (1998) and Nouria et al. (2008) used the seismic coefficient kv to represent the vertical seismic inertia force; Ling et al. (1997), Ling (2001), and Ingles et al. (2006), assumed that there was a relationship between vertical and horizontal accelerations; Zhang et al. (2015) analyzed the stability of seismic slopes using actual vertical ground motion records. Although each method has its advantages, the use of the actual horizontal and vertical ground motion records for analyzing the dynamic stability of slopes is more in line with actual situations.

Experimental results have shown that the strength envelopes of virtually all geomaterials are characteristically nonlinear in the σ_n–τ stress space, particularly in the range of small normal stresses (e.g., Charles and Soares 1984; Maksimovic, 1989). Nonlinearity is closer to the nature of geomaterials than linearity, and many researchers (e.g., Maksimovic, 1989; Chen and Liu, 1990; Jiang et al., 2003; Baker, 2004; Anyaegbunam, 2015) have shown that the nonlinear failure criterion plays a significant role in slope stability. The effects of the nonlinear strength criterion and earthquakes on slope stability have been extensively investigated (Zhang and Chen, 1987; Collins et al., 1988; Drescher and Christopoulos, 1988; Maksimovic, 1989; Chen and Liu, 1990; Baker, 2004; Li, 2007; Fu and Liao, 2010; Zhao et al., 2010a, 2010b, 2015; Li and Cheng, 2012; Anyaegbunam, 2015). However, few researchers have analyzed the seismic displacement of slopes based on the nonlinear M–C strength criterion.

Current studies show that the upper bound limit analysis is widely used in stability analyses of soil and rock structures. Employing this analysis, complicated stress calculations can be avoided; only velocity modes and energy dissipations are considered. The present study adopted the upper bound limit analysis to assess the effect of the vertical earthquake component on the seismic displacement of slopes based on the nonlinear M–C strength criterion. A calculation model was developed based on the Newmark sliding rigid block model. The ‘‘external tangent method” was also employed to obtain the instantaneous shear strength parameters of the nonlinear M–C failure criterion. In addition, two different approaches were used to analyze the effect of the vertical acceleration on the permanent displacement of slopes under conditions of linearity and nonlinearity with four sets of typical seismic ground motion records.

2. Upper bound analysis of seismic slopes

2.1. Basic assumptions

In this paper, the magnitude and direction of the earthquake forces vary as a result of the positive and negative accelerations of actual seismic ground records. A horizontal earthquake force in the sliding direction is assumed when the value of the horizontal acceleration at a point is positive. Similarly, a downward vertical earthquake force is assumed when the value of the vertical acceleration at a point is positive. To simplify the study, the following assumptions are made based on the results of previous relevant studies (Chang et al., 1984; Chen and Liu, 1990; Cai and Bathurst, 1996; You and Michalowski, 1999; Michalowski and You, 2000; Nouria et al., 2008; Leschinsky et al., 2009):

(1) Plane strain conditions are assumed.
(2) The soil mass of the slope is an ideal rigid-plastic body; it satisfies the nonlinear M–C strength criterion and obeys the associated flow rule.
(3) The pore water pressure (as considered in geotechnical engineering) and the changes in shear strength parameters of the soil mass due to the seismic action are ignored.
(4) The principal stress and principal strain axes are coaxial.
(5) Earthquake forces are considered; they act on the center of gravity of a sliding soil mass.

2.2. General nonlinear failure criterion and tangential technique

This study adopted the following nonlinear M–C failure criterion (Zhang and Chen, 1987; Collins et al., 1988; Drescher and Christopoulos, 1988), as illustrated in Fig. 1: