Engineering Geology 204 (2016) 53–64

Contents lists available at ScienceDirect

Engineering Geology

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

Regional-scale co-seismic landslide assessment using limit equilibrium analysis

Angela Saade [a], Grace Abou-Jaoude [a,*], Joseph Wartman [b]

[a] Department of Civil Engineering, Lebanese American University, Lebanon
[b] Department of Civil and Environmental Engineering, University of Washington, Seattle, United States

ARTICLE INFO

Article history:
Received 15 July 2015
Received in revised form 4 February 2016
Accepted 12 February 2016
Available online 13 February 2016

Keywords:
Regional
Co-seismic
Landslide assessment
Slip surfaces
Newmark sliding block
Geographic Information System

ABSTRACT

Traditionally, regional assessment of seismic slope stability has been done using the infinite slope-rigid sliding block analysis. A major disadvantage of this approach is the resulting overestimation of the critical acceleration of the slope due to the underlying assumption of a predefined slope failure plane, and consequently the underestimation of hazard areas prone to sliding. In this paper, we present a modified approach for assessing seismic slope instabilities using a model based on limit equilibrium analysis and circular slip surfaces with no restriction to any predefined slope failure plane. For this purpose, we conduct a parametric study to identify the relationship between the critical acceleration of the slope, the slope angle, and the slope shear strength parameters. We model typical slopes in the Rocscience software *SLIDE* using Bishop's limit equilibrium method to identify the critical accelerations that corresponds to a failure plane with factor of safety equal to one. The critical accelerations were plotted against the variables in the parametric study and the best fit equations were obtained. The proposed approach was developed for global application but it was tested using the well-documented co-seismic landslide database of the 1994 Northridge, CA earthquake. The predicted sliding areas were compared to the inventory of landslides that were triggered in the Val Verde region in Los Angeles by the earthquake. Qualitative and quantitative assessments of the proposed model clearly show its advantages in predicting potential sliding areas.

1. Introduction

Earthquakes are among the most destructive of all geologic hazards. In addition to causing shaking-induced damage to buildings and infrastructure systems, earthquakes are associated with a range of secondary effects, including the initiation of landslides. These *earthquake-induced*, or *co-seismic* landslides can extend across thousands of square kilometers and result in both human and capital losses (Evans et al., 2009; Shou et al., 2011; Collins et al., 2012; Alfaro et al., 2012; Xu et al., 2014; Has and Nozaki, 2014; Tang et al., 2015; Delgado et al., 2015; among others). Recent examples include the 2013 M_w 6.6 Lushan, China earthquake (Xu et al., 2014, 2015), the 2011 M_w 9.0 Tohoku, Japan earthquake (Wartman et al., 2013; Wang et al., 2014), and the 2008 M_w 7.8 Wenchuan, China earthquake (Dai et al., 2011; Tang et al., 2011; Huang and Li, 2014; Wang et al., 2014; Zhang et al., 2014), each of which triggered many thousands of landslides across tens of thousands of km^2. It is estimated that between September 1968 and June 2008, co-seismic landslides were responsible for over 70,000 casualties (Marano et al., 2010).

As a regional-scale phenomenon, co-seismic landslide potential is traditionally assessed within a Geographic Information Systems (GIS) framework (e.g. Jibson et al., 2000; Khazai and Sitar, 2000; McCrink, 2001; Jibson, 2007; Jibson, 2011; Dreyfus et al., 2013). Most GIS-based assessments adopt Newmark's (1965) sliding block model to estimate earthquake-induced permanent displacements. For regional-scale assessments, regression models are often used to estimate sliding block displacements in lieu of site-specific time-history analyses (e.g. Wilson and Keefer, 1985; Romeo, 2000; Bray and Travasarou, 2007; Jibson, 2007; Saygili and Rathje, 2008). To conduct a sliding block analysis, one must first compute the *yield* or *critical acceleration* (a_c) of a slope (Newmark, 1965). This is conventionally done by modeling slopes as infinitely long planes (i.e., the infinite slope assumption, e.g. Duncan et al., 2014). However, earthquake reconnaissance studies reveal a wide range of earthquake-induced landslide styles occurring in both soil and rock units. For example, Keefer (1984) identified fourteen types of landslides in a study of 40 earthquakes and grouped these into three major categories: disrupted falls, coherent slides and lateral spreads. Disrupted falls, such as rock slides, detach from steep slopes, are generally shallow, and constitute a significant majority of observed landslides. In contrast, coherent slides are deep, near-circular failure surfaces that mainly occur on moderate slopes. Lateral spreads involve fluid-like flow and move on gentle slopes (Wilson and Keefer, 1985; Wartman et al., 2013). This suggests that the infinite slope assumption may be an oversimplification in many settings.

* Corresponding author.
E-mail address: grace.aboujaoude@lau.edu.lb (G. Abou-Jaoude).

http://dx.doi.org/10.1016/j.enggeo.2016.02.004
0013-7952/

In this paper, we present a modified approach for assessing co-seismic landslide hazards using regressed values of limit equilibrium-derived estimates of a_c based on Bishop's (1955) method. Bishop's (1955) limit equilibrium model for circular slip surfaces has been shown by Loukidis et al. (2003) and Li et al. (2008), among others, to provide reasonably good results when compared to more rigorous numerical upper and lower bound solutions for a range of slope inclinations and material strength conditions. Loukidis et al. (2003) and Li et al., (2009; 2010; 2011) developed simplified solutions to assess the seismic stability of soil and rock slopes using the Mohr–Coulomb (MC) failure criterion and the 2002 generalized Hoek–Brown (HB) failure criterion, respectively. The MC criterion has been widely used in geotechnical engineering for modeling both cohesionless and cohesive soil material, while the HB criterion is often used for modeling the strength of a wide range of rock masses (Marinos et al., 2005, Marinos and Hoek, 2000) [in this work we do not consider materials that loose significant strength during earthquake shaking, such as liquefiable soils that may fail in lateral spreading]. We develop generalized equations for a_c based on a parametric assessment that considers material strength and slope inclination as variables. A plane strain slope model implemented in the Rocscience code SLIDE (Version 6.0) was used to conduct simulations of slopes inclined between 15° and 70°. General equations for a_c of a slope and for a set of strength parameters were generated in a two-step regression analysis. An advantage of this approach is that it is based on the limit equilibrium analysis of a generalized slope geometry. Having equations proposed for two yield criteria enhances the methods versatility and allows the user to define the strength parameters of a geologic unit using the most appropriate strength criteria.

We apply our approach to a region affected by landsliding during the 1994 Northridge, CA earthquake, and compare the results with the well-documented inventory of landslides from this event (Harp and Jibson, 1995, 1996). We also contrast the predictions of our modified approach with those obtained from a traditional infinite slope-based analysis.

2. Seismic slope stability model

2.1. Use of the conventional pseudo-static approach

Conventional pseudo-static analyses of slopes represent the transient, dynamic destabilizing earthquake inertial forces as static forces applied to a limit equilibrium model. This widely used approach simplifies earthquake ground-motion to simple horizontal and vertical seismic coefficients, k_h and k_v, respectively (Kramer, 1996; Khazai and Sitar, 2000; Loukidis et al., 2003; Li et al., 2009). These coefficients represent the ratio of the acceleration of the slope to the acceleration of gravity (g). The vertical coefficient k_v is commonly neglected when assessing slope displacement (Kramer, 1996; Kim and Sitar, 2004; Jibson, 2011). In this study, seismic slope stability is assessed using the critical horizontal seismic coefficient k_c, a value that corresponds to a factor of safety of the slope equal to unity under seismic loading. When the critical value is approached, the factor of safety drops below 1 and earthquake-induced sliding occurs. We will hereinafter refer only to the critical acceleration, a_c, which corresponds to the critical horizontal seismic coefficient (k_c) multiplied by the acceleration of gravity (g).

2.2. Use of Bishop's (1955) simplified limit equilibrium method

Various methodologies, such as the limit equilibrium, finite element, and limit analysis methods, have been adopted in order to calculate the a_c of a slope (Loukidis et al., 2003; Li et al., 2009; Jibson, 2011). Limit equilibrium methods provide a reasonable estimation of the factor of safety with minimal computational cost (Duncan, 1996; Loukidis et al., 2003; Li et al., 2009). We adopted Bishop's (1955) simplified method as it has been shown to produce results that generally lie within the numerical upper and lower bound solutions, with modest analysis effort (Loukidis et al., 2003; Li et al., 2008).

2.3. Applicability of the Mohr–Coulomb and the generalized Hoek–Brown failure criteria

The MC linear failure criterion is widely used in geotechnical engineering applications and is mostly suitable for soil-like material. Model parameters (i.e., cohesion and friction angle) may be obtained from standard laboratory strength tests, assumed based on experience, or in some cases back-calculated from a well-characterized slope failure. The generalized HB criterion is a non-linear criterion that is commonly used to estimate the strength of rock masses. It is based on the Geological Strength Index (GSI) classification system, which relies on an engineering geology description of a rock mass. The GSI index is estimated from visual examination of the rock mass exposed in outcrops. It is used in conjunction with appropriate values of the rock-type constant m_i and the unconfined uniaxial compressive strength σ_{ci}. Once a GSI index is determined, a set of empirically developed equations are used to estimate the rock-mass properties. Hoek et al. (2002) present the most recent update on these empirical equations and discuss how one can estimate equivalent MC strength parameters for the rock-mass properties. Marinos et al. (2005) discuss in further detail the applicability of the GSI classification system in a wide range of soft to hard and even heterogeneous rock masses.

The use of these two failure criteria is based on the work of Loukidis et al. (2003) and Li et al. (2008), who found that the MC criterion resulted in good agreement between the limit analysis and limit equilibrium solutions for soil slopes less than 45°, but that MC parameters can significantly overestimate the factors of safety for steep slopes when compared to the numerically bounded solution. The overestimation is greatest for slopes steeper than 45° (16.8% for 60° slopes and 34.3% for 75° slopes, on average). Li et al. (2008) also found that when the HB failure criterion was used for steep slopes, the results were significantly improved when compared with the limit analysis output (maximum overestimation of 4% in extreme cases of very strong material at a slope inclination of 75°). Li et al. (2008) proposed a series of equations to estimate the equivalent MC parameters for two slope categories; slopes less than 45° and slopes greater than or equal to 45°.

The MC and the HB failure criteria were used in this study to represent soil and rock materials encountered across regional-scales. It is important to note, however, that the applicability of the proposed approach in this study is subject to the same limitations that underpin both the MC and the HB criteria. The equations derived by Li et al. (2008) will be used, when needed, to calculate the equivalent parameters for a particular set of material strengths.

2.4. Proposed model

A simple generic slope model with fixed dimensional parameters (Height $H = 30$ m and a unit weight $\gamma = 23$ kN/m^3) served as the basis for the parametric study (Fig. 1). To ensure broad applicability, the equations of a_c were normalized with respect to the term γH. The practice of normalizing with respect to γHhas been discussed by

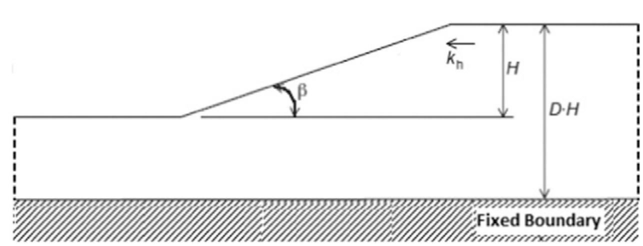

Fig. 1. Geometrically unified simple slope model used in *SLIDE*.