ARTICLE IN PRESS
ENGEO-03803; No of Pages 8
Engineering Geology xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Engineering Geology

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

An analytical solution to slip buckling slope failure triggered by earthquake

Shengwen Qi [a,b,*], Hengxing Lan [a,c], Jinyu Dong [d]

[a] Key Lab. of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[b] Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Canada
[c] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
[d] College of Resources and Environment, North China University of Water Conservancy and Hydroelectric Power, Zhengzhou, China

ARTICLE INFO

Article history:
Accepted 3 June 2014
Available online xxxx

Keywords:
Analytical solution
Buckling failure
Tangjiashan coseismic landslide
Energy equilibrium theory

ABSTRACT

Slip buckling failure often occurs in slopes intersected by a set of discontinuities with approximately parallel to the surface. Post-earthquake investigations indicate that some slip buckling failures occurred during 2008 Wenchuan event. However, it is still difficult to evaluate the slip buckling failure triggered by earthquakes. In this paper, we give a thorough mechanical analysis to slip buckling slope, and present an analytical solution on slip buckling slope failure which fully considers both the effect of earthquake and pore water pressure based on energy equilibrium theory. Then we apply the methodology to Tangjiashan landslide. Comprehensive retrospective study indicates that Tangjiashan landslide is a typical buckling failure case triggered by Wenchuan earthquake. The application shows that the analytical solution can be used to evaluate the stability of the slope with potential buckling failure during earthquake.

1. Introduction

Slip buckling slope failure often occurs when the slope is intersected by a set of discontinuities approximately parallel to the surface forming a slabbing. The failure mechanism suggests that the slope dips more steeply than the angle of internal friction of slabs formed by discontinuities (Cavers, 1981). It often initiates as a translational sliding along a weak interlayer on the upper slope and then creates a bulge by buckling slabs near the toe of the slope. Buckling slope failure is often observed in a stratified sedimentary rock slope. It can also occur in a metamorphic rock slope, for example, in a slope dominated by phyllites where cleavage or schistosity is significant and regular (Froldi and Lunardi, 1995).

A number of studies have been conducted to understand the slip buckling slope failure mechanism. Cavers (1981) developed simple formulae for three possible cases of buckling: flexural buckling of plane slopes, three hinge-buckling of plane slopes and three-hinge buckling of curved slopes, and analyzed flexural buckling failures using the concept of Euler's formula. Sun (1988) treated the buckling of rock slabs as a beam stability problem using the elastic theory, and suggested an energy equilibrium principle for solving this problem. Pant and Adhikary (1999), and Adhikary et al. (2001) investigated the mechanism of flexural buckling failure of foliated rock slopes, using both explicit and implicit finite element numerical models in AFENA code (a large deformation Cosserat continuum model). Qin et al. (2001) presented a catastrophe cusp model to study the failure mechanisms of the slip-buckling slope, and suggested the important role of the historical evolutionary process of slope on its failure. Recently, Pereira and Lana (2013) analyzed a buckling failure occurring in an open pit mine based on software Phase2. The effect of discontinuity strength such as stiffness and cohesion, and the in situ stress on the buckling failure was presented.

Post-earthquake investigations indicate that slip buckling slope failures often occur during earthquake. For example, slip buckling slope failure was observed in a huge landslide triggered by 2008 Wenchuan earthquake shown in Fig. 1 and the Chiu-fen-erh-shan landslide triggered by Chi-Chi earthquake (Wang et al., 2003). However, the effect of earthquake on such failure mode has not been well understood by previous researches i.e. Cavers (1981), Sun (1988), Pant and Adhikary (1999), and Adhikary et al. (2001). In this paper, an analytical solution on slip buckling slope failure is presented by considering the effect of earthquake as well as the pore water pressure. A typical case-Tangjiashan landslide triggered by Wenchuan Earthquake on May 12, 2008 is analyzed.

2. Mechanical model and analytical solution to the slip-buckling slope failure

Similar to Cavers (1981), Sun (1988) and Qin et al. (2001), the mechanical model of rock slope slab buckling is simplified as a beam stability problem in this paper, which is rational since both the length and the width of the rock slab are far larger than its thickness. The mechanical model is shown in Fig. 2, in which l is the buckling segment of the slab and l_0 is the driving segment of the slab, P is the residual driving force of unit width along the interlayer, q is the gravitational load intensity, k_1 and k_2 represent the component of seismic coefficient in the normal and parallel direction to the slab. According to energy

---

[*] Corresponding author at: Key Lab. of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.
E-mail address: qishengwen@mail.iggcas.ac.cn (S. Qi).

http://dx.doi.org/10.1016/j.enggeo.2014.06.004
0013-7952/© 2014 Elsevier B.V. All rights reserved.

Please cite this article as: Qi, S., et al., An analytical solution to slip buckling slope failure triggered by earthquake, Eng. Geol. (2014), http://dx.doi.org/10.1016/j.enggeo.2014.06.004

Fig. 1. One case of buckling failure triggered by 2008 Wenchuan earthquake.
Adapted from Yang (2011).

equilibrium, an analytical solution is derived for on the slip buckling slope failure taking into account both the effect of earthquake and pore water pressure expressed as follows.

The work done by residual driving force of P is

$$\Delta T_1 = P\Delta \tag{1}$$

where Δ is the shortening amount of the slab induced by P, and can be calculated as

$$\Delta = \int_0^l \sqrt{(1+(y')^2)}dx - l \tag{2}$$

where y is the deflection curve, and y is the first derivatives of y.

Making Taylor expansion and omitting second order and higher, Δ can be expressed as

$$\Delta = \frac{1}{2}\int_0^l (y')^2 dx. \tag{3}$$

Substituting Eq. (3) into Eq. (1),

$$\Delta T_1 = \frac{1}{2}P\int_0^l (y')^2 dx. \tag{4}$$

The work done by the self weight of the buckling segment is

$$\Delta T_2 = \frac{1}{2}\int_0^l q(l-x)(y')^2 \sin\alpha dx \tag{5}$$

where α is the slope angle.

The work done by pore water pressure is

$$\Delta T_3 = \begin{cases} \int_0^{l_1} y r_w (l_1 - x)\sin\alpha dx, l_1 < l \\ \int_0^{l} y r_w (l_1 - x)\sin\alpha dx, l_1 \geq l \end{cases} \tag{6}$$

where r_w is the water density and l_1 is the distribution length of the groundwater along the slab.

The work done by seismic force is

$$\Delta T_4 = \int_0^l k_1 q y dx + \frac{1}{2}\int_0^l k_2 q(l-x)(y')^2 dx. \tag{7}$$

The strain energy caused by the buckling stored in the slab is

$$\Delta u_1 = \frac{1}{2}\int_0^l EI(y'')^2 dx \tag{8}$$

where E and I are the elastic modulus and the moment of inertia of the slab respectively according to elastic theory (Timoshenko and Goodier, 1970), and y'' is the second derivatives of y.

The potential energy increment caused by the self-weight of the beam is equal to

$$\Delta u_2 = \int_0^l q y \cos\alpha dx. \tag{9}$$

Energy equilibrium is expressed as,

$$\Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 = \Delta u_1 + \Delta u_2. \tag{10}$$

According to elastic theory (Timoshenko and Goodier, 1970), the deflection curve y can be rewritten as

$$y = a_1\left(1 - \cos\frac{2\pi x}{l}\right) + a_2\left(1 - \cos\frac{4\pi x}{l}\right), \quad 0 \leq x \leq l \tag{11}$$

where a_1 and a_2 are the coefficients.

If $x > l$, $y = 0$.

Thus

$$\Delta T_1 = \frac{P}{2}\left(a_1^2\frac{2\pi^2}{l} + a_2^2\frac{8\pi^2}{l}\right) \tag{12}$$

Please cite this article as: Qi, S., et al., An analytical solution to slip buckling slope failure triggered by earthquake, Eng. Geol. (2014), http://dx.doi.org/10.1016/j.enggeo.2014.06.004