Geotextiles and Geomembranes 42 (2014) 515–524

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

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

Evaluation of oblique pullout resistance of reinforcements in soil wall subjected to seismic loads

Yufeng Gao [a], Shangchuan Yang [a, *], Yongxin Wu [a], Dayong Li [b], Fei Zhang [a]

[a] Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, No. 1, Xikang Road, Nanjing 210098, China
[b] College of Civil Engineering & Architecture, Shandong University of Science and Technology, No. 579, Qianwangang Rd., Huangdao, Qingdao, 266590, China

ARTICLE INFO

Article history:
Received 3 October 2013
Received in revised form
6 July 2014
Accepted 27 July 2014
Available online 15 August 2014

Keywords:
Geosynthetics
Reinforced soil wall
Horizontal slice method
Pseudo-static seismic analysis
Safety factor
Pullout resistance

ABSTRACT

Pullout resistance is one of the most important factors governing seismic stability of reinforced soil walls. The previous studies on the seismic stability of reinforced soil walls have focused on the axial resistance of the reinforcement against the pullout. However, the kinematics of failure causes the reinforcement to be subjected to the oblique pullout force and bending deformation. Considering the kinematics of failure and bending deformation of the reinforcement, this paper presents a pseudo-static seismic analysis for evaluating the pullout resistance of reinforcements in soil wall subjected to oblique pullout forces. A modified horizontal slice method (HSM) and Pasternak model are used to calculate the required force to maintain the stability of the reinforced soil wall and shear resistance mobilized in the reinforcements, respectively. In addition, this paper studies the effect of various parameters on the pullout resistance of the reinforcements in soil wall subjected to seismic loads. Results of this study are compared with the published data and their differences are analyzed in detail.

1. Introduction

Reinforced soil structures meeting modern design standards were found slightly damaged in violently shaken areas where major seismic events happened recently, for example, in the 1994 Northridge earthquake (Sandri, 1997; White and Holtz, 1997), 1995 Great Hanshin-Awaji earthquake (Tatsuoka et al., 1995), 1995 Hyogo-ken Nanbu earthquake (Tatsuoka et al., 1997; Koseki, 2012), 2004 Niigataken-chuetsu earthquake, 2007 Noto-hanto earthquake, 2007 Niigataken-chuetsu-oki earthquake, 2008 Iwate-Miyagi-nairiku earthquake, 2011 Off the Pacific Coast of Tohoku earthquake (Koseki, 2012). Besides having performed well during strong earthquakes, reinforced soil structures have the advantage of low cost (Koerner and Soong, 2001). Therefore reinforced soil structures have been extensively used. Their seismic behavior has been attracting more attention and studied recently by many methods, such as laboratory tests (e.g. Huang, 2013; Srilatha et al., 2013; Wang et al., 2011; Huang et al., 2011; Izawa and Kuwano, 2011; Nakajima et al., 2010), numerical simulations (e.g. Lee and Chang, 2012; Liu et al., 2011) and theoretical analyses (e.g. Vahedifard et al., 2013; Mojallal et al., 2012; Basha and Babu, 2012).

Theoretical approaches for the seismic analysis of reinforced soil walls mainly adopt the pseudo-static approach representing the effect of earthquake by the static force. Analytical techniques mainly include the limit analysis method and the limit equilibrium method. Assuming different distribution modes of reinforcement strength, Michalowski (1998) applied the kinematic upper bound theorem of limit analysis to evaluate the required strength and length of reinforcement to prevent slopes from collapsing. Ausilio et al. (2000) calculated the reinforcement force necessary to prevent failure and obtained the yield acceleration of slopes subjected to earthquake loads within the framework of the pseudo-static method using the kinematic theorem of limit analysis for different modes of failure. Limit equilibrium method is also extensively applied for the analysis. Ling et al. (1997) extended the static equilibrium approach for the design of reinforced soil slopes and walls (Leshchinsky et al., 1995) to the seismic case and presented the seismic stability analysis of reinforced soil slopes considering the horizontal acceleration and a tolerable displacement against sliding for different modes of failure. Ling and Leshchinsky (1998) investigated the effect of vertical acceleration on the seismic stability of reinforced soil structures. Based on the Mononobe–Okabe limit equilibrium method, Bathurst and Cai

* Corresponding author. Tel.: +86 25 83787287; fax: +86 25 83713073.
E-mail addresses: yfgao66@163.com (Y. Gao), ysc4711@gmail.com (S. Yang), yxwuhhu@163.com (Y. Wu), ldy@sdust.edu.cn (D. Li), jefferygsls@gmail.com (F. Zhang).

http://dx.doi.org/10.1016/j.geotexmem.2014.07.011
0266-1144/

(1995) proposed the procedure to conduct the pseudo-static seismic analysis of geosynthetic reinforced segmental retaining walls. Baker and Klein (2004a, 2004b) optimized the design of reinforced soil retaining structures by the limit equilibrium technique. Using a pseudo-static method based on a ‘multi-wedge’ failure mechanism, Huang and Wang (2005) calculated seismic displacements of the Tanata wall and investigated the effect of vertical acceleration on its seismic displacements and stability. They found that the contribution of the ratio of vertical to horizontal accelerations of the Tanata wall is small.

Pullout resistance is one of the most important factors governing seismic stability of reinforced soil walls. The previous studies on reinforced soil walls have focused on the axial resistance of the reinforcement against the pullout (Rowe and Ho, 1993; Jewell, 1992; Sobhi and Wu, 1996). The experimental results and direct observations, however, show that because of kinematics of failure, the reinforcement is subjected to an oblique pullout force which causes bending deformation of the reinforcement (Shewbridge and Sitar, 1989; Bergado et al., 2000). Then this bending deformation increases the pullout capacity of the reinforcement. Hence, it is necessary to consider the kinematics of failure and the consequent bending deformation of the reinforcement for the pullout resistance evaluation of reinforced soil walls.

Considering the kinematics of failure, Reddy et al. (2008) analyzed the seismic stability of reinforced soil wall with inextensible sheet reinforcements. Taking into account the increase in tension due to the transverse displacement of reinforcement, they developed the model proposed by Madhav and Umashankar (2003) to calculate the pullout resistance of reinforcements in the soil wall. However, this model does not establish equilibrium equations for the tolerable final bent deformed shape of the reinforcement (Fig. 1(a, b)). Fig. 1(a) illustrates that the anchored portion of the ith reinforcement embedded at depth h_i is subjected to a transverse force, P_i, at Point A due to transverse displacement $w_{i,L}$. Fig. 1(b) shows the deformed profile of the anchored portion of the ith reinforcement and the forces acting on it. P_i results in a higher shear

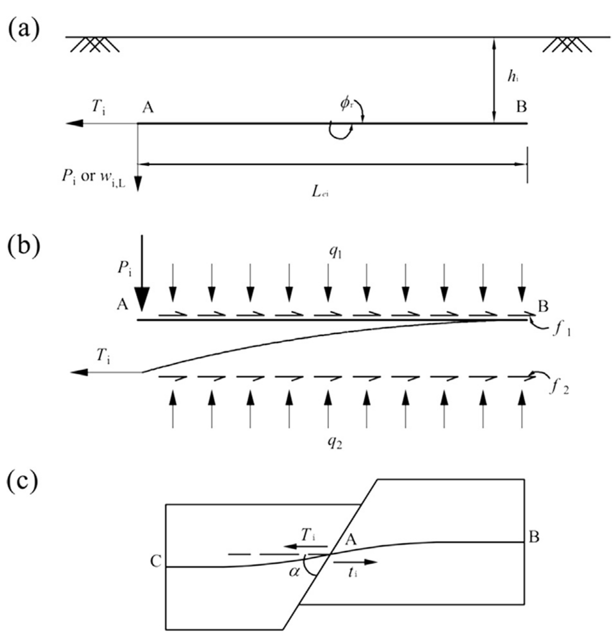

Fig. 1. Schematic of model used in Reddy et al. (2008) (a) Single sheet reinforcement subjected to transverse force, (adapted from Madhav and Umashankar, 2003), (b) deformed profile and forces acting on the reinforcement (adapted from Madhav and Umashankar, 2003), (c) Kinematics of failure of horizontal soil slice with reinforcement.

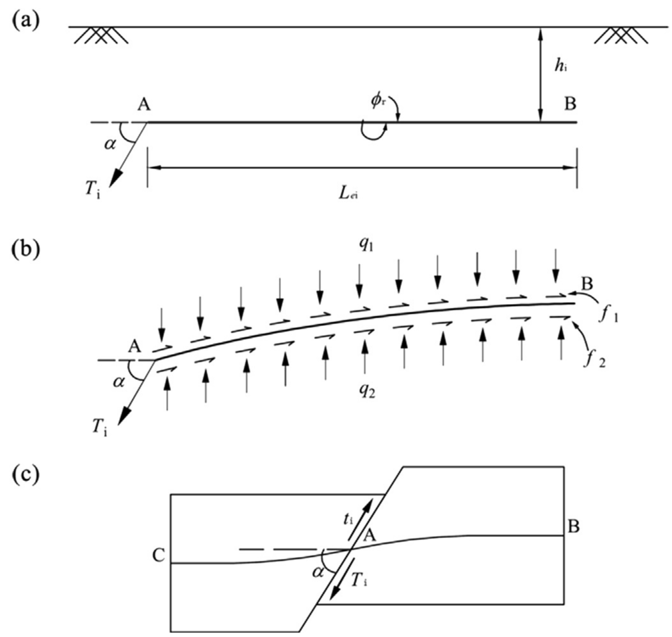

Fig. 2. Schematic of model used in this study (a) Single sheet reinforcement subjected to oblique force, (adapted from Patra and Shahu, 2012), (b) deformed profile and forces acting on the reinforcement (adapted from Patra and Shahu, 2012), (c) Kinematics of failure of horizontal soil slice with reinforcement.

resistance mobilized in the ith layer of the reinforcement. But when the kinematics of failure occurs, reinforcement deforms due to the oblique pullout force (Fig. 2(a)), and the forces acting on the anchored portion of the deformed reinforcement are shown in Fig. 2(b). Besides, they modified the HSM proposed by Shahgholi et al. (2001) to calculate the required force to maintain the stability of the reinforced soil wall under seismic loading (Fig. 1(c)). But the force is not assumed to be oblique when the kinematics of failure occurs (Fig. 2(c)).

In this study, the HSM proposed by Nouri et al. (2006) is modified and Pasternak model (Patra and Shahu, 2012) is employed. Based on the pseudo-static method, the pullout resistance of inextensible sheet reinforcements in soil wall is analyzed considering the kinematics of failure. In calculating the required force to prevent the failure of reinforced soil wall subjected to seismic loads using HSM, the orientation of the force is set to be oblique considering the kinematics of failure. The corresponding results are compared with both Reddy et al. (2008) and the results that only consider the axial resistance of the reinforcement against the pullout obtained in this study.

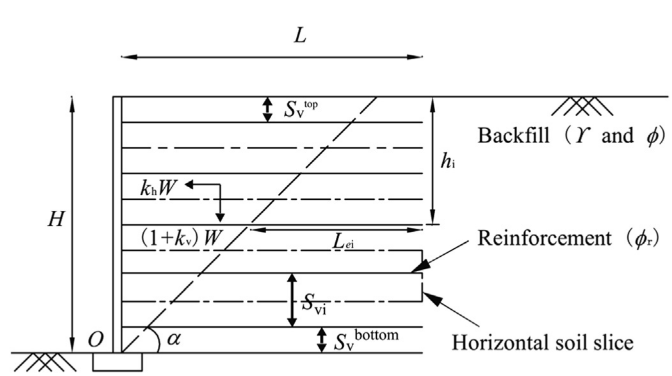

Fig. 3. Geometric and geotechnical characteristics of reinforced soil wall with planar failure surface and horizontal slices.