ARTICLE IN PRESS

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ScienceDirect

Soils and Foundations xxx (2018) xxx–xxx

www.elsevier.com/locate/sandf

Seismic motion response and fragility analyses of cantilever retaining walls with cohesive backfill

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Received 18 May 2017; received in revised form 14 December 2017; accepted 17 December 2017

Abstract

The seismic motion response of a cantilever retaining wall with cohesive and cohesionless backfill materials was evaluated using fully dynamic analysis based on finite difference method. The dynamic analysis was validated based on experimental test results and then compared to analytical and empirical correlations based on Newmark sliding block method. Seven different earthquake events and the backfills with low to high levels of cohesion were considered. Nonlinear regression analyses were carried out to provide correlations between free-field peak ground acceleration (PGA) and maximum relative displacement of the retaining wall. These results were compared to results from empirical and analytical methods. Furthermore, fragility analyses were conducted to determine the probability of damage to the retaining wall for different free-field PGAs and backfill cohesions. It is demonstrated to what extent a small amount of cohesion in backfill material can influence displacement of the retaining wall and probability of damage in seismic conditions.

Keywords: Retaining wall; Dynamic analysis; Fragility analysis; FLAC; Backfill cohesion; Newmark sliding block method

1. Introduction

Several retaining wall deformations and failures have been reported during historical earthquakes (Fang et al., 2003; Ko et al., 2017; Lai, 1998; Ling et al., 2001; Shakya, 1987). The most well-known method for predicting the seismic deformation of retaining wall is known as Newmark sliding block method (Newmark, 1965). The Newmark sliding block method requires the acceleration time history of an earthquake in the free-field. However, as the acceleration time history might not be available for a practical design, some investigators including Richards and Elms (1979) developed empirical correlations to evaluate maximum retaining wall displacement in seismic conditions. The Richards and Elms empirical correlation (R&E) has been suggested in different design guidelines including Army Corps (Whitman and Liao, 1985) and AASHTO LRFD Bridge Design Specifications (AASHTO, 2007). In a more recent study conducted by Anderson et al. (2008) and as part of The National Cooperative Highway Research Program (NCHRP) study, an updated correlation was provided based on various Newmark analyses. The updated NCHRP equation has been embedded in the recent guidelines including Caltrans (Ertugrul 2013). More advanced Newmark based pseudo-static methods have also been developed to evaluate the sliding deformation of the retaining walls (e.g., Biondi et al., 2014; Conti et al., 2013). However, it is noteworthy that the above-mentioned studies only consider the sliding deformation of the retaining wall and the rotational and tilting deformation are neglected. Some investigators including Nadim

Peer review under responsibility of The Japanese Geotechnical Society.
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https://doi.org/10.1016/j.sandf.2018.02.010
0038-0806/

and Whitman (1984), Rafnsson (1991), Prakash et al. (1995), and Wu and Prakash (2001) adopted analytical approaches to predict the seismic deformation of the retaining walls considering tilt and rotation of the retaining wall. However, due to the complexity of these analytical procedures, the approaches have not been adopted in design guidelines for practical purposes.

The deformational behavior of gravity and cantilever retaining walls in seismic conditions, have been studied numerically (Agusti and Sitar, 2013; Corigliano et al., 2011; Green et al., 2008; Green and Ebeling, 2003; Stamatopoulos et al., 2006; Wilson and Elgamal, 2010; Wu and Prakash, 2001) and experimentally (Green and Ebeling 2003; Huang et al., 2009; Nakamura 2006; Richards et al., 1996; Stamatopoulos et al., 2006; Wilson and Elgamal 2010, 2015; Zeng and Steedman 2000). The main scope of most of these studies was evaluating sliding and rotational displacement of retaining wall systems during earthquake events. In a few studies (Agusti and Sitar 2013; Nakamura 2006; Wilson and Elgamal 2010, 2015), seismic earth pressure and retaining wall motion responses were also investigated. In addition, Huang et al. (2009) and Wu and Prakash (2001) proposed a wall displacement criterion for identifying the level of damage for seismic performance of retaining walls.

There are some limitations with these studies. For example, most of the mentioned studies focused on retaining walls with cohesionless backfill materials. A few studies (Agusti and Sitar 2013; Latifi et al., 2016; Mikola et al., 2014; Osouli and Zamiran 2017; Wilson and Elgamal 2015; Zamiran and Osouli 2014, 2015) considered backfill cohesion, however, their main focus was not displacement behavior of retaining walls. Moreover, specific backfill cohesion was selected in these studies. Therefore, the effects of cohesion variation on seismic response of the walls were not considered. In addition, only limited number of seismic events and shaking intensities were used in these studies.

There is limited information about the seismic deformational response of retaining walls with cohesive backfills. However, field inspections by Kapuskar (2005) show low to high level of cohesiveness in backfill materials. The study conducted by Caltrans (Kapuskar 2005) investigated 20 different bridge sites in the State of California. It was found that in 18 cases, the backfill material of bridge abutments contains some level of cohesiveness. In 9 cases, backfill materials with up to 95 kPa cohesion were observed.

The other critical factor is the stochastic nature of earthquake and its related damages, which is often characterized by the probability of occurrence or failures. For example, fragility analyses have been used to evaluate the probability of failures of different structures (Baker 2015) and caisson quay walls (Ichii 2004; Jafarian et al., 2014). However, there has been a lack of knowledge in determining the fragility functions of cantilever retaining wall structures especially with cohesive backfills.

In this study, the seismic motion behavior of cantilever retaining walls with different backfill cohesions will be explored using fully dynamic analysis (FDA). The numerical modeling procedure will be validated based on centrifuge tests conducted by Agusti and Sitar (2013). To evaluate the performance of the retaining wall, seven different input motions with different acceleration intensities will be considered. The displacements for various free-field peak ground accelerations (PGA) will be analyzed. Fragility analyses will be conducted to evaluate the probability of damage based on different earthquake accelerations.

2. Methodology

A series of FDA analyses based on finite difference method in FLAC (Itasca 2011) is used to identify the displacement characteristics of the retaining walls. In the first step, the centrifuge study conducted by Agusti and Sitar (2013) on retaining walls with cohesive backfill material was used to verify the numerical modeling methodology (i.e., Analysis Group A in Table 1). The free-field motion responses of the backfill and the wall displacement during FDA were compared with centrifuge results of Agusti and Sitar (2013).

The validated model was utilized to identify the effect of 0, 10, and 30 kPa cohesion in backfills to cover a common range of cohesions reported for retaining wall backfills by Caltrans (Kapuskar 2005). Backfill materials were modeled in unsaturated conditions. For these scenarios, labeled as Analysis Group B in Table 1, the Imperial Valley earthquake (1979) was introduced to the model as the earthquake input motion. The horizontal relative wall displacement (RWD) time history was monitored at the top and bottom of the wall. The RWD time history was determined by subtracting the horizontal ground displacement variation in free-field condition from the horizontal total wall displacement at the desired location (Green et al., 2008). The maximum RWD during the earthquake is recorded and is compared with the results of analytical solutions including Newmark sliding block method, R&E, and NCHRP correlations (Anderson et al., 2008; Newmark, 1965; Richards and Elms, 1979).

In order to evaluate seismic deformation of the retaining walls based on different input motions, Analysis Group C shown in Table 1 was conducted. Seven different earthquake loadings including Imperial Valley (1979), Loma Prieta (1989), Chi-Chi (1999), Kobe (1995), Northridge (1994), Hollister (1961), and Friuli (1976) were considered. For each event, different input acceleration intensities were applied to the model to correlate the maximum RWD based on free-field PGA variations. The Amplification Factor (AF) was used as a representative of input acceleration intensity. The AF of 100% shows an earthquake with the input PGA of 0.25 g. In these series of analyses, backfills with three different cohesions including 0, 10, and 30 kPa were considered.

Finally, the motion response from the mentioned seven different earthquakes with various input acceleration intensities and backfill cohesions were used to evaluate the fail-

Please cite this article in press as: Zamiran, S., Osouli, A., Seismic motion response and fragility analyses of cantilever retaining walls with cohesive backfill, Soils Found. (2018), https://doi.org/10.1016/j.sandf.2018.02.010