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Research Paper

The effect of backfill cohesion on seismic response of cantilever retaining walls using fully dynamic analysis

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ABSTRACT

The analyses of retaining walls in California showed many backfills are coarse material with some cohesion. In this investigation, seismic response of cantilever retaining walls, backfilled with dirty sandy materials with up to 30 kPa cohesion, is evaluated using fully dynamic analysis. The numerical simulation procedure is first validated using reported centrifuge test results. The validated methodology is then used to investigate the effects of three earthquake ground motions including Kobe, Loma Prieta, and Chi-Chi on seismic response of retaining walls. In addition, the input peak ground acceleration values are varied to consider a wide range of earthquake acceleration intensity.

1. Introduction

Current seismic design criteria for retaining wall structures suggested by different organizations are based on estimating seismic earth pressure of the wall using analytical solutions (e.g. [1,10]. Different guidelines including AASHTO and Caltrans consider pseudo-static analytical solutions to identify seismic earth pressure [1,10]. The first analytical attempt as a pseudo-static method to evaluate seismic earth pressure of retaining walls was suggested by Okabe [27] and the method was verified in retaining walls with unsaturated and cohesionless soil material by Mononobe and Matsuo [22] using shake table test results. The method developed by these investigators is known as Mononobe-Okabe (MO) method and is still widely used to determine seismic earth pressure of retaining walls. MO procedure is an extension of Coulomb theory and is based on limit equilibrium method and assumes an occurrence of a failure wedge in the backfill. MO method considers the earthquake acceleration is uniform in the backfill and is applied to the center of gravity of the failure wedge.

There are also many studies that evaluated the total seismic earth thrust (P_{ae}) experimentally [2,3,6,25,28,33] and numerically [6,9,12,15,14,30,31,40,42]. Specifically, Seed and Whitman [33], hereafter abbreviated as S&W, conducted different centrifuge tests on retaining walls with cohesionless backfill materials and provided a simple equation for determining P_{ae}, which linearly correlates with horizontal earthquake peak ground acceleration (PGA). Their experimental-based estimation has been used in design guidelines for evaluating P_{ae}, e.g., US Army Corps of Engineers [39]. It is worth mentioning that the earthquake acceleration intensities for the mentioned numerical and experimental studies were limited to PGA ground motions of 0.2g to 0.4 g. In most of these studies, the cohesion factor of backfills and hysteretic behavior of soil were also neglected.

Guidelines by AASHTO and state Departments of Transportations suggest the use of granular materials as backfill for retaining wall constructions as they provide better drainage capacity and have less sensitivity to swell or shrinkage problems [1,10,23]. However, according to field observations in several cases, backfill materials have a various amount of cohesion [18]. Kapuskar [18] conducted field observations of more than 100 retaining wall and abutment backfills used in 20 different bridge sites in the State of California. It was concluded that out of 20 bridge sites, 15 of them had sandy backfills with low plasticity fines that had cohesion up to 95 kPa.

Seismic response of retaining walls considering backfill cohesion has been taken into account analytically [11,29,36,35,37]. Most of these approaches were developed based on an extension of MO method with consideration of backfill cohesion, wall adhesion, and tension cracks in cohesive backfill materials. The MO-based methods have restrictions to be used for backfills with different soil layers and complex geometries. Therefore, analytical methods based on trial wedge procedure has been proposed for backfills with various layers of soil or complex geometries [5].

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In addition to analytical solutions, there are some experimental and numerical investigations have also been conducted to evaluate the effects of backfill cohesion on seismic response of retaining walls [2,21,40,41,43,44]. The limitations of these studies are: (1) the wall response with a variation of backfill cohesion was not considered; (2) the P_{ae}, its point of action, and induced moment under full seismic analyses were not considered; (3) the representative hysteretic damping and shear reduction of the backfill materials have not been considered. Also, these studies focused on the effect of either single soil cohesion parameter or single PGA.

In this paper, seismic response of retaining walls is evaluated for cantilever walls with cohesive sandy backfill materials via fully dynamic analysis (FDA). A constitutive model accounting the hysteretic behavior of soil during dynamic loading excitation is utilized. A validated numerical approach based on centrifuge test results is used to conduct the FDA. The effect of three earthquake ground motions and backfill with various cohesions on seismic earth pressures, total seismic earth thrust coefficient (K_{ae}), incremental seismic earth thrust coefficient (ΔK_{ae}), the location point of action of P_{ae}, and wall moment variations during the shaking event are studied. The results of FDA are compared to estimations based on current analytical solutions. Finally, recommendations are provided for considering the effects of backfill cohesion in seismic response of cantilever retaining walls.

2. Methodology

For the investigation of the seismic response of retaining walls with cohesive sandy backfill materials, plain strain two-dimensional numerical modeling in Fast Lagrangian Analyses of Continua (FLAC Version 7.0) was conducted [17]. It is worth noting that two-dimensional analysis is commonly used for such analyses. For retaining walls with uniform height along the construction alignment, the results of two-dimensional plane strain models are in reasonable agreement with three-dimensional models as well as experimental results [12]. Instead of pseudo-static approach or equivalent linear method, a FDA is used to conduct earthquake analysis modeling. As a first step, the simulation methodology was validated using an experimental centrifuge study with cohesive silty backfill carried out by Agusti and Sitar [2]. Once the numerical approach was validated, it was used for further analyses discussed herein for an idealized 6-m high cantilever retaining wall with various backfill cohesions.

The retaining wall with a cohesive sandy backfill that has the cohesion of 30 kPa was subjected to three different earthquake ground motions (i.e., Loma Prieta, 1989, Chi-Chi, 1999, and Kobe, 1995) to investigate the effects of different earthquake events on seismic response of the retaining wall. It should be noted that the input PGA of all earthquakes is normalized to 0.25 g to have a reasonable comparison between the mentioned events. For PGA normalization to 0.25 g, the original acceleration for each event was multiplied by 0.25 g and divided by its initial PGA value. Therefore, the final PGA of updated acceleration for all events was 0.25 g. In order to study the effects of backfill cohesion variation, a series of analyses were conducted using backfill materials with 0, 15, and 30 kPa cohesion representing sandy backfills with zero to medium level of cohesiveness, respectively, according to field observations conducted by Kapuskar [18]. The earthquake selected for this phase of the study was Loma Prieta 1989. Different input acceleration intensities of Loma Prieta earthquake were applied to the base of the model to obtain a wide range of free-field PGA (PGA_{ff}) values. Table 1 shows a summary of all the numerical modeling analyses. In this table, for an easier comparison, the amplification factor (AF) is used to show the input PGA intensities. The AF of 100% represented an earthquake with input PGA of 0.25 g for this study and the AF of 200% represents the input PGA of 0.5 g.

The simulations were conducted under drained and unsaturated conditions. For each analysis, K_{ae}, ΔK_{ae}, the point of action of P_{ae}, and maximum moment of the wall during the earthquake were monitored. The K_{ae}, ΔK_{ae}, and point of action were studied both at the wall-backfill interface and at 3-m distance from the wall, where the heel is located. Finally, the results of numerical modeling were compared to those of analytical [5,22,27] and experimental [2,33] based methods.

3. Numerical modeling

3.1. Model geometry

For all analyses, a conventional retaining wall with a height of 6 m was used as shown in Fig. 1 based on Agusti and Sitar [2] centrifuge tests [2]. The geometry of centrifuge test simulation in the numerical modeling was selected according to the prototype model, which was 36 times of the actual centrifuge model wall [2]. Finite difference mesh with a size of 50 cm for each element was selected considering the criterion of Kuhlemeyer and Lysmer [19] to avoid wave distortion during seismic wave transmission through the medium. Based on this criterion, the element size should be smaller than one-eighth to one-tenth of the wavelength of the highest frequency component of the input earthquake [19].

3.2. Material properties and constitutive model

In order to consider the dynamic characteristics of soil during seismic motions, the UBCHYST constitutive model developed by Naesgaard [24] was used as shown in Table 2. This constitutive model allows to simulate the hysteretic behavior of soil including damping, material softening, and shear modulus reduction with an increase in strain during dynamic analysis [24]. Examples of shear modulus curves for cohesionless soils [32] and soils containing cohesion [38] can be seen in Fig. 2. Using UBCHYST, the shear modulus curve for a specific soil can be introduced to the model per Eq. (1) according to Naesgaard [24]:

$$G = G_{\max}\left(1 - \frac{\eta_1}{\eta_{1f}} R_f\right)^n \cdot Mod_1 \tag{1}$$

where G is the shear modulus of the soil for a given cycling loop of dynamic loading, and G_{max} is the maximum shear modulus of the soil. The ratio of shear stress to the vertical stress of the soil element (σ_s/σ_v) is defined as η. The parameter η_1 or η_{1f} are determined by subtraction of stress ratios of a given cycling loop and the next cycle or the final failure loop, respectively. The constants of R_f, n, and Mod_1 suggested by Naesgaard [24] are 1, 2, and 0.6–0.8, respectively, and are used in this study. To verify the obtained modulus reduction and soil damping curves with experimental correlations in the literature [32,38], cyclic shear tests were conducted in FLAC using UBCHYST model as shown in Fig. 2. According to this figure, the shear modulus curve obtained from the numerical modeling of cyclic shear tests for soils with zero cohesion and some cohesion are in close agreement with Seed and Idriss [32] results for cohesionless soils and Vucetic and Dobry [38] results for cohesive materials, respectively. A summary of soil properties and UBCHYST constants of all phases of the study is provided in Table 2.

Although the hysteretic properties in UBCHYST include the damping behavior of the soil medium, a small amount of Rayleigh damping is also needed to damp the oscillation and noises due to the low-level frequency component of an earthquake event [17]. Based on the FLAC manual [17], for selecting the Rayleigh damping parameters, the critical damping ratio of 0.2% and the predominant