6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

DEM Simulation of the Seismic Response of Gravity Retaining Walls

U. El Shamy[1], A. Patsevich[2]

ABSTRACT

In this study, analysis of the seismic response of a soil-retaining wall system is performed based on a three-dimensional microscale framework utilizing the discrete element method. The granular soil deposit is idealized as a collection of spherical soil particles; the retaining wall is simulated as a rigid block composed of clumped particles to yield the physical characteristics of an actual retaining wall. The model accounts for the effects of nonlinear soil behavior, possible separation between the retaining wall and backfill, and dynamic soil-wall interaction. The computational approach is able to capture essential dynamic response patterns. For instance, the simulation captured permanent wall displacement accumulation as well as rotational stiffness degradation as shaking progresses. Wall motion was amplified relative to the amplitude of input motion. Computed dynamic active backfill thrust acting on the wall was comparable to the theoretical value of active earthquake pressure calculated using the M-O method.

Introduction

Earth retaining structures, such as retaining walls, are commonly used in seismically active areas. Several historical earthquakes have resulted in significant permanent deformation and failure of retaining structures. Seismic analysis of retaining walls is a challenge as wall movements and pressures depend on several factors such as the response of the underlying soil, the response of the backfill, inertial forces of the wall, and the characteristics of the input motion. Only a few well-documented case histories involving field measurements of wall response are available, thus most of the current understanding of the dynamic response of retaining walls has come from model tests and numerical analyses.

Various simplified models have been used in order to determine effects of the earthquake on the retaining structures. Okabe (1926) and Mononobe and Matsuo (1929) developed the basis of pseudo-static analysis (known as the M-O method) of seismic earth pressures on retaining structures. Further development on the Mononobe-Okabe method has been done by Richards and Elms (1979) and Whitman and Liao (1985) when they employed Newmark's sliding block procedure in evaluations of earthquake induced displacements of gravity retaining walls. Despite all the improvements and modifications to the Newmark's sliding block method, the rigid block approach lacks the ability of modeling the seismic response of the backfill behind a retaining wall and, consequently, the associated effects on earthquake-induced displacements and dynamic wall thrust (Nadim and Whitman, 1983; Kramer and Smith, 1997; Wartman et al., 2003).

[1]Associate Professor, Civil and Environmental Engineering Department, Southern Methodist University, Dallas, TX, USA, uelshamy@lyle.smu.edu
[2]Graduate Student, Civil and Environmental Engineering Department, Southern Methodist University, Dallas, TX, USA, apatsevich@smu.edu

Design based on pseudo-static approach is generally considered conservative, since even when the safety factor drops below one the soil structure could experience only finite displacement rather than a complete failure. Analysis techniques used to determine the response of retaining walls to the dynamic loading typically implement multiple assumptions and simplifications limiting the application of the solution to a specific case that is being investigated. In this paper, a new approach for investigating the complex behavior of retaining walls under a seismic excitation using the Discrete Element Method (DEM) is presented. The proposed approach accounts for soil nonlinearity, dynamic soil-wall interaction, and possible separation between the wall and the surrounding soil during dynamic excitation.

Model Description

A microscale-based approach is adopted in this study to model the soil-retaining wall system. The soil deposit is modeled as a collection of granular particles using DEM, resting on a rigid base. The motion of a discrete particle is dictated by the translational and angular momentum equations of motion. The retaining wall is idealized as a rigid body composed of clumped particles to simulate the physical characteristics of a real-life retaining wall. That is, regardless of the forces acting upon it, the block will not break apart. The contact forces between the clumped particles are not accounted for during the DEM calculation cycle. However, the interactions between the clumped particles and soil particles composing the deposit are considered. Since the clumped particles behave as a rigid body, the translational and rotational equations of motion are sufficient to describe its motion. More details of employed model maybe found in Zamani and El Shamy (2012) and Patsevich (2015).

Computational Simulation

The proposed approach was employed to investigate the response of a three degrees of freedom retaining wall on a dry granular deposit. Fig. 1 shows the deposit used in the simulation. Use was made of the high g-level concept commonly used in centrifuge testing to reduce the dimensions of the domain that needed to be filled with particles and to benefit from the shorter time scaling law within which the simulation can be conducted (Iai et al., 2005). Furthermore, periodic boundaries were employed in the lateral direction parallel to the direction of shaking to reduce the size of the simulation. The other two lateral boundaries and the base of the deposit were modeled as a rigid wall. The two walls in a lateral direction were created at a significant distance away from the retaining wall (18 m from the back of the wall and 6 m in front of the wall) in order to decrease any possible effects of the lateral boundaries. After the boundaries of the domain were established, the soil-wall system was created within the domain.

Soil particles constituting the domain were generated and allowed to settle under gravity. New particles constituting the retaining wall were created and clumped together in a fashion that will keep the particles together no matter what force is acting on them. The retaining wall is composed of four walls to represent a box with a width of 0.02 m, a length of 0.06 m and a height of 0.09 m (width = 1 m, length = 3 m, height = 4.5 m in prototype units). These walls were made of clumped particles with a diameter of 2 mm and a center-to-center spacing of 0.5 mm (particles overlap to provide a relatively flat surface for the walls). The angle of friction between the wall and the surrounding soil was assumed to be 18°. The density of the concrete consisting retaining wall in prototype units was assumed to be 2400 kg/m^3, which resulted in each particle composing the wall to have a density of 2960 kg/m^3, and the total mass of the retaining wall to be 0.26 kg (32,500 kg in prototype units).The retaining wall was then installed on top of the base layer and more particles were generated to form the backfill. Wall stability checks were performed under static conditions. Computational data are summarized in Table 1 along with the computed static safety factors for wall stability. Additional computational details and information about model generation maybe found in Patsevich (2015).

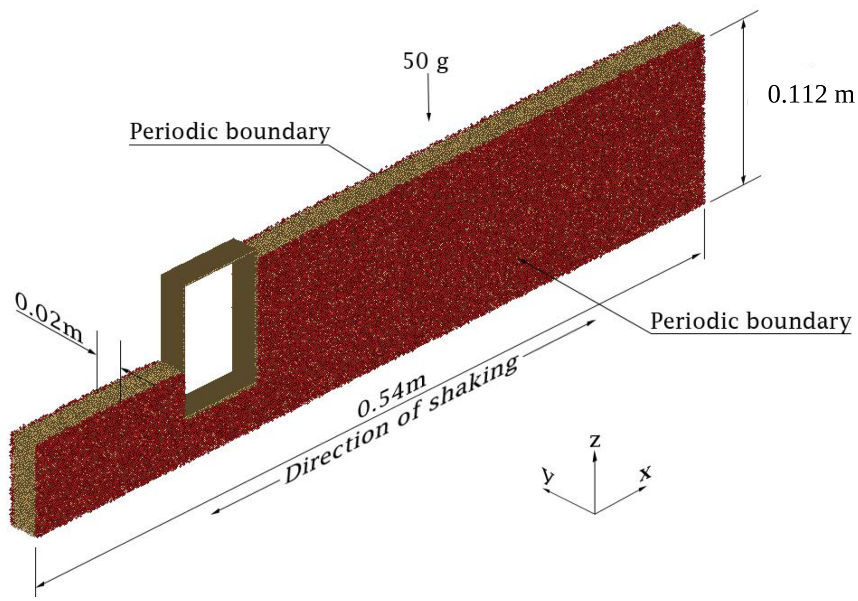

Figure 1. Granular deposit and retaining wall structure as modeled in DEM simulations

Table 1. Simulation data in model units.

Soil Deposit	
Number of particles	379,735
Particle diameter	1.2 to 1.8 mm
Density of solid particles	2650 kg/m^3
Particle normal/shear stiffness	5×10^5 N/m
Friction coefficient	0.5
Shear wave velocity	133 m/s
Average friction angle ϕ	27°
Retaining Wall	
Length	60 mm
Width	20 mm
Height	90 mm
Static Factors of Safety	
Bearing capacity	4.6
Sliding	6.2
Overturning	2.1

The system was then subjected to a dynamic excitation applied to the bedrock and lateral boundaries perpendicular to the direction of shaking, and the responses of soil deposit and retaining wall were monitored. This application of the input motion is somewhat similar to shaking an experimental model retaining wall in a rigid box. The dynamic excitation followed a sinusoidal pattern with a frequency of 2 Hz and consisted of three stages that lasted a total of eight seconds. During the first three seconds of the simulation the amplitude of the input motion was gradually increasing to reach the maximum amplitude of 0.1g at 3 seconds, then for the next four seconds the amplitude of the input motion stayed constant, and finally within one second the amplitude of the input motion gradually decreased to zero. The location of the rigid lateral boundaries was far enough to produce free-field behavior half way between the wall and the right boundary. This was verified by computing the amplification factor of the input motion as it propagates to the surface and comparing it to that from classical wave propagation theory. The computed one was about 1.35 compared to the theoretical value of 1.2.

Wall Response

Figure 2 shows the time-history of the acceleration of the input motion compared to the acceleration of the center of gravity of the wall. The response of the retaining wall is amplified relative to the input motion on the negative side of the acceleration record, i.e., when wall is moving away from the backfill. It can be noted that the inertial forces of the retaining wall have resulted in a phase lag between the motion of the retaining wall and the input motion applied to the bedrock. The maximum acceleration of the wall under current loading parameters was determined to be 0.15g, which is 1.5 times larger than the amplitude of the input motion.

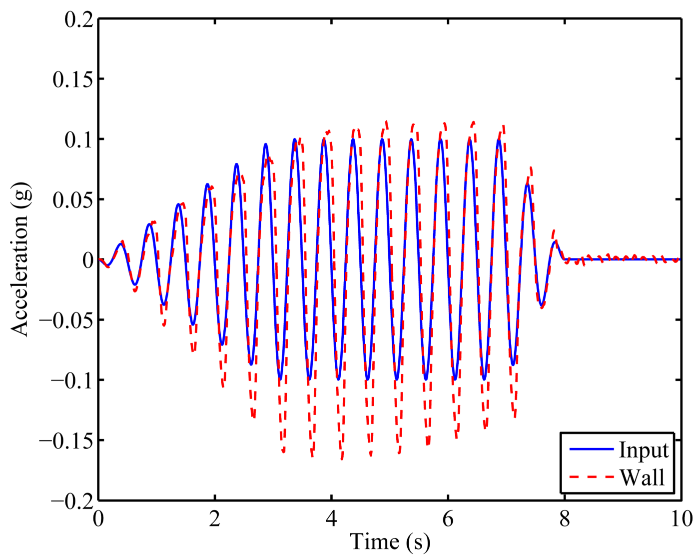

Figure 2. Time histories of wall and input accelerations

Time-histories for total soil thrust on front and back faces of the wall during the simulation (Fig. 3) show how the total thrust was changing throughout the simulation. According to the theoretical calculations based on Coulomb earth pressure theory, minimum active thrust resulting from the backfill is 47.4 kN/m, while the computed initial thrust on the back of the wall is approximately 65.2 kN/m. Dynamic active soil thrust was calculated to be about 57.8 kN/m using the M-O method (using the characteristics of the input motion and a k_h value of 0.1). The total thrust on the back side of the wall during the simulation is varying between 62 kN/m and 84 kN/m (Fig. 3). Values of the backfill thrust acting on the wall at the time instances when the wall is moving away from the backfill, i.e., lowest values of the total thrust, are comparable to the theoretical value of active earthquake pressure calculated using the M-O method. It can indicate that the wall experienced movement that resulted in the development of an active wedge when the wall was moving away from the backfill during the simulation. Comparatively, when the wall was moving towards the backfill, i.e., highest values of the total thrust, it did not produce enough movement to mobilize the full passive resistance of the soil in the backfill.

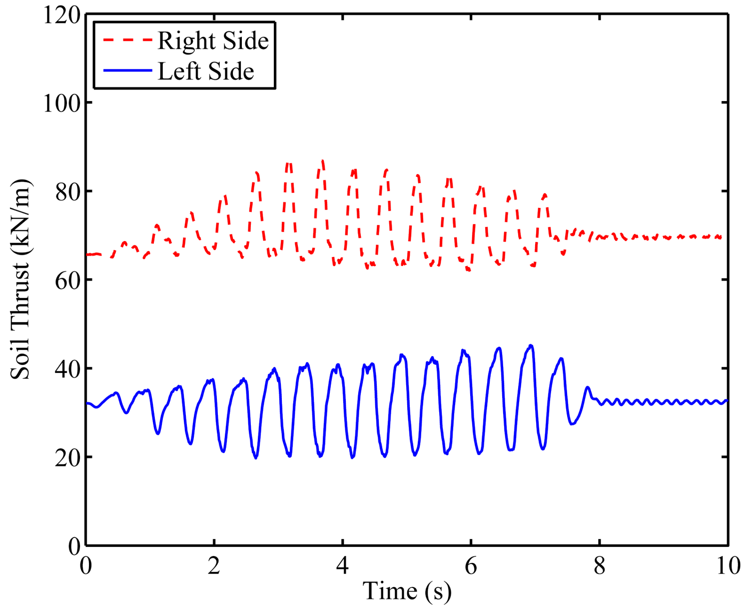

Figure 3. Time histories of soil thrust on the retaining wall

On the front side of the wall, the initial soil thrust of 32.3 kN/m is not close to either minimum or maximum theoretical values of static soil thrust (active=6.7 kN/m and passive = 95.5 kN/m, respectively). During the simulation, the soil thrust on the wall front stays within the range of 20 kN/m to 44 kN/m. Using the M-O method, the minimum and maximum theoretical values were calculated to be 8.7 kN/m and 92.0 kN/m, respectively. Neither the minimum nor maximum values of the soil thrust time history are close to their theoretical values, indicating that the deposit in front of the wall does not experience significant deformation to develop a full passive wedge when the wall is moving towards it, and the wall does not move away from it far enough to develop an active wedge at any time during the simulation. It can be noted that the soil thrust on the back of the wall (Fig. 3) has a 180° phase shift with the soil thrust on front of the wall indicating a side to side movement of the wall during the simulation. When the wall is moving away from the backfill, the soil thrust decreases on the back of the wall and increases on the front side of the wall.

Similarly to the soil thrust on the side of the retaining wall, forces acting on each particle in the base of the wall were tracked during the simulation allowing to determine the pressure distribution on the base of the wall. Special attention was paid to the pressure on the edges of the base wall, as rocking mode of motion would indicate development of higher pressures at the edges of the base during the dynamic loading. A portion equal to 10% of the length of the base wall was taken into consideration when monitoring pressure development on the tip and toe of the retaining wall (Fig. 4). Initially, the pressure under the toe is higher than the pressure under the heel due to initially higher thrust from the backfill of the wall. The edges of the base of the wall experience change in stress as time progresses. The 180^o phase shift in the pressure was observed between the edges due to rocking. When the wall rotates away from the backfill the pressure on the tip increases and the pressure on the toe decreases, and when the wall rotates toward the backfill the pressure on the tip decreases when the pressure on the toe increases. Maximum value of the soil pressure developed at the tip of the wall is around 220 kPa, which is much smaller than predicted bearing capacity, therefore significant vertical displacement is not expected.

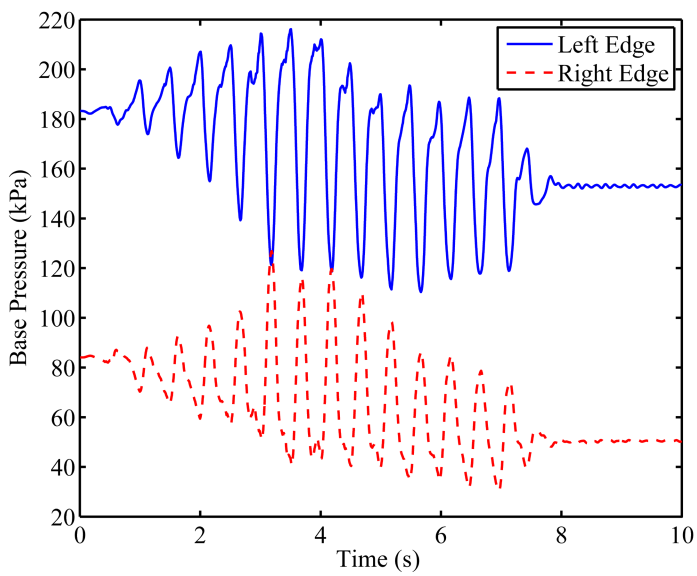

Figure 4. Time-history of pressure on left and right edges of the base of the wall

Figure 5 shows horizontal, vertical and rotational displacement time histories of the wall. Horizontal displacement of the wall experiences cyclic as well as permanent modes of deformation as time progresses. These types of movement can be clearly seen in the displacement plot (Fig. 5a). It can be seen that displacement of the retaining wall consists of the accumulated displacement that increases as the simulation progresses and cyclic displacement that represents the side-to-side motion during every cycle. The total horizontal displacement the wall has experienced is 42 mm in prototype units, which is a little over the theoretical value of 40 mm using the method proposed by Richards and Elms (1979). The total settlement of the wall during the simulation was less than 1 cm in prototype units, and the total rotation of the retaining wall is less than 0.01 rad.

Changes in the magnitude and location of the soil thrust as well as changes in the distribution of the pressure on the base of the wall resulted in out of balance horizontal and vertical forces, as well as rocking moment at the center of the base of the wall. These forces were calculated throughout the simulation using the methodology presented by Zamani and El Shamy (2012).

Figure 6 shows the moment-rotation relationships for this simulation. The moment-rotation history (Fig. 6a) shows high negative values of the moment were produced by the pressure from the backfill and caused the wall to rotate away from it. The accumulation of the rotational displacement during the simulation can be observed. The cyclic moment-cyclic rotation plot (Fig. 6b) shows that the moment-rotation relationship is nonlinear throughout the simulation, with rotational stiffness degrading as shaking progresses.

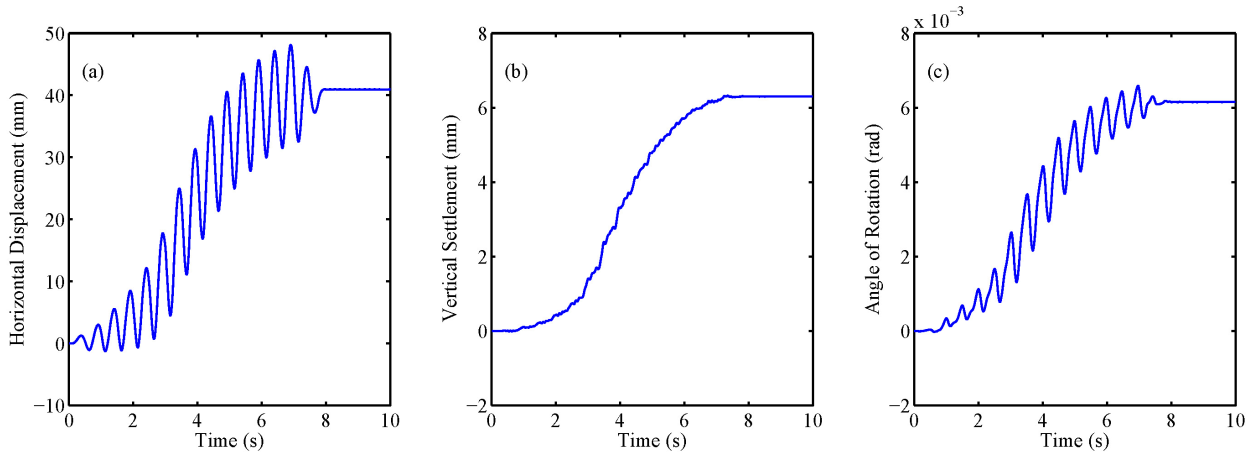

Figure 5. Time histories of (a) horizontal displacement, (b) vertical settlement, and (c) wall rotation

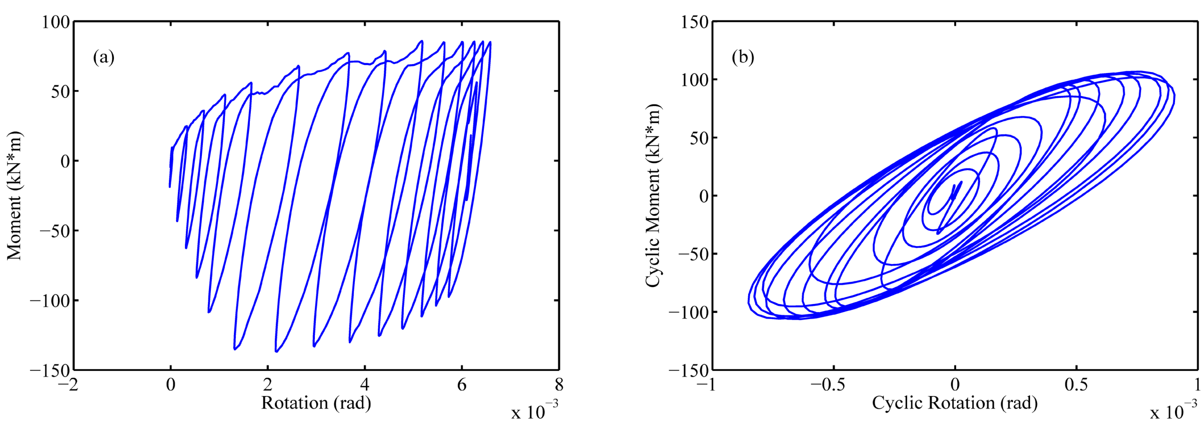

Figure 6. Plots of (a) moment-rotation, and (b) cyclic moment-rotation

Conclusions

A DEM microscale approach is proposed to investigate the seismic response of the soil-retaining wall system in time-domain while taking into the account nonlinear behavior of the soil, possible separation between wall base and soil caused by rocking, sliding of the wall with respect to the ground, and dynamic soil-wall interaction. The results presented herein highlight the strength of the proposed DEM-based technique and its ability to model large-scale boundary value problems. The trends observed in the conducted simulations were similar to those of the existing experimental and analytical results. For instance, the simulation captured permanent wall displacement accumulation as well as rotational stiffness degradation as shaking progresses. Wall motion was amplified relative to the amplitude of input motion. Dynamic backfill thrust acting on the wall at the time instances when the wall is moving away from the backfill were comparable to the theoretical value of active earthquake pressure calculated using the M-O method. However, when the wall was moving towards the backfill it did not produce enough movement to mobilize the full passive resistance of the soil in the backfill. Results of additional simulations that examine the system response to various motion amplitudes and frequencies (including the response near resonance) are currently being compiled and will be published elsewhere.

Acknowledgments

This research was partially supported by the US Army Corps of Engineers Engineer Research and Development Center, grant number W9132V-13-C-0004. This support is gratefully acknowledged.

References

Iai, S., Tobita, T., and Nakahara, T. Generalized scaling relations for dynamic centrifuge tests. *Geotechnique* 2005: **29**: 105–118.

Kramer, S. and Smith, M. Modified Newmark model for seismic displacements of compliant slopes. *Journal of Geotechnical and Geoenvironmental Engineering* 1997, ASCE; **123**(7): 635-644.

Mononobe, N. and Matsuo, H. On the determination of earth pressures during earthquakes. *Proceedings of the World Engineering Congress* 1929; 179-187, Oakland.

Nadim, F. and Whitman, R. Seismically induced movement of retaining walls. *Journal of the Geotechnical Engineering Division* 1983; **109**(7): 915-934.

Okabe, S. General theory of earth pressures. *Journal of the Japan Society of Civil Engineering* 1926; **12**(1).

Patsevich, A. *Discrete-element method analysis of seismic response of gravity retaining walls*. M.S. Thesis, Southern Methodist University, Dallas, TX, USA 2015.

Richards, R. and Elms, D. Seismic behavior of gravity retaining walls. *Journal of the Geotechnical Engineering Division* 1979, ASCE; **105**(GT4): 449-464.

Wartman, J., Bray, J., and Seed, R. Inclined plane studies of the Newmark sliding block procedure. *Journal of Geotechnical and Geoenvironmental Engineering* 2003, ASCE; **129**(8): 673-684.

Whitman, R. and Liao, S. *Seismic design of gravity retaining walls*. Report No. Miscellaneous Paper GL-85-1, US Army Corps of Engineering 1985.

Zamani, N., and El Shamy, U. (2012). Analysis of the seismic response of soil-foundation-structure systems using a microscale framework. *Soil Dynamics and Earthquake Engineering* 2012; **43**: 398-412.