Scale Model Shake Table Testing of Seismic Earth Pressures in Soft Clay

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ABSTRACT

There is much uncertainty in seismic earth pressures for basement wall design and retaining wall design in clay soil. The research presented herein uses a scale model testing platform on a 1g shake table to measure the distribution and magnitude of seismic earth pressures for the prototype soil conditions of San Francisco Young Bay Mud (YBM). Similitude scaling of the dynamic soil properties, the wall dimensions, and the input time histories (among other variables) affords accurate modeling of the prototype scale wall. For basement conditions, inertial soil structure interaction (SSI) effects are included in the experiments. Care is taken to properly mimic static lateral stress conditions of the walls to achieve active or at-rest conditions for the respective wall designs prior to shaking. Results for a wall of prototype 3m height experiencing a large ground motion is shown and compared to current earth pressure design recommendations.

INTRODUCTION

Recent changes to the design codes have required the consideration of seismic earth pressures in retaining wall and basement wall design. Although retaining wall failures have been observed primarily in waterfront areas in recent earthquakes, away from the waterfront no basement walls or retaining wall failures have been observed due to seismic earth pressures. (Lew et al 2010). This observation is rather peculiar because some of the observed walls, designed only for static earth pressures, have performed quite well during a seismic event.

These observations have led researchers to question the validity of existing analytical methods of evaluating seismic earth pressures. Following the great Kanto Earthquake of 1923 in Japan, Mononobe and Matsuo (1929) and Okabe (1924) developed a method based on Coulomb's theory of static earth pressures to evaluate seismic earth pressure on a retaining wall. The method, often called the M-O method, was developed for dry cohesionless material that yields sufficiently for minimum active earth pressures to develop on the retaining wall. Seed and Whitman (1970) reexamined the M-O method and proposed a simplified equation that separates the active earth pressure coefficients into a static component and a dynamic component. The M-O method as modified by Seed and Whitman method has proven to be the most widely used method for evaluating seismic earth pressures.

Previous Research

The Mononobe-Okabe method is not only the most widely used method for evaluating seismic earth pressures, but also the most criticized. The M-O method was based on scale model research from yielding retaining walls with cohesionless backfills, but due to its simplicity has been applied to rigid retaining wall design such as basement walls and walls retaining soils with cohesion. Due to the apparent misuse of the method, Ostadan and White (1998) stated that "the M-O method is one of the most abused methods in geotechnical practice."

Nakamura (2006) used centrifuge testing to reevaluate the accuracy of the Mononobe-Okabe method. Nakamura's work suggests that the earth pressure distribution on a retaining wall is not triangular as assumed in the M-O method, and reports a list of other observations contrary to M-O. Nakamura (2006) summarizes that for retaining wall design the M-O method is inappropriate for calculating seismic earth pressures because the predicted seismic behavior of the retaining wall and the backfill soil does not match actual seismic behavior.

Al Atik and Sitar (2007) performed a suite of centrifuge tests to further evaluate the M-O method. They found that seismic earth pressures can be neglected for peak horizontal accelerations below 0.3g. They note that even higher accelerations can be resisted providing that the retaining wall is designed with an adequate factor of safety. They found that the maximum dynamic earth pressures exhibited a triangular distribution with depth, and that the observed triangular distribution appeared analogous to that of static earth pressures. Al Atik and Sitar also observed that that maximum moment of the wall and the maximum earth pressure were out of phase.

Current Investigation

This research measures seismic earth pressures behind basement walls and retaining walls in normally consolidated (NC) clay soil conditions using a 1g scale model testing approach. This follows on previous research by Meymand (1998), Crosariol (2010), Moss et al. (2010), Moss et al. (2011), Moss & Crosariol (2011), utilizing 1g shaking table tests with appropriately scaled dynamic clay soil conditions to approximate prototype scale behavior. Lew et al (2010) documents the current understanding of seismic earth pressures from a design perspective for basements and retaining walls.

TESTING PLATFORM

In order to produce valid empirical scale model tests on the shake table, similitude analysis of the important variables that affect the overall performance must be evaluated. Factors such as the dynamic soil strength, structural period, dynamic structural response, and time step of the ground motion must be scaled according to similitude laws as was described for this type of dynamic testing by Meymand (1998) and shown in Table 1. Fig. 1 shows the shake table located at Cal Poly that is used in these tests.

Figure 1. Testing platform consists of shake table and flexible wall barrel. Flexible wall barrel is composed of the four corner posts with universal joints at the top and bottom, top and bottom rings, and the barrel wall. The wall is composed of rubber membrane which is confined by Kevlar straps. Cross braces are removed during shaking for free articulation and proper 1-D response.

The main testing equipment is a flexible wall barrel that mimics free field site response under seismic loading on the shake table. The flexible wall barrel has been validated through table testing and 1-D equivalent linear numerical analysis in a recently completed research project (Crosariol, 2010; Moss et al., 2010).

The flexible wall barrel is filled with a model soil mix using an industrial scale mixer shown in Figure 2. The prototype soil in this research is San Francisco young bay mud (YBM). The similitude scaling parameter (λ) is set at 10th scale for this series of test. The dynamic strength is the primary soil variable scaled for this test. A mix of kaolinite, bentonite, fly ash, and water are used in specific volumes to achieve the proper scaled strength to hit the target prototype strength. The mix has an average 110% water content, and the target undrained strength is 4 kPa which gives a typical dynamic undrained strength ratio (s_u/σ_v') for YBM. This mix of the soil was developed, tested, and validated through the previous research by Meymand (1998) and Crosariol (2010) among others.

Table 1. Prototype-Model Similitude

Variable	Scale Factor	For λ=10
Soil Density	1	1
Force*	λ^3	1000
Stiffness*	λ^2	100
Modulus	λ	10
Acceleration	1	1
Shear wave Velocity	$\lambda^{1/2}$	3.16
Soil Damping	1	1
Poisson's ratio	1	1
Time	$\lambda^{1/2}$	3.16
Frequency	$\lambda^{-1/2}$	0.316
Length	λ	10
Stress	λ	10
Strain	1	1
Flexural Rigidity*	λ^5	100000
Dimensionless Quantities	1	1

The 1-D shake table has a 4500 kg payload capacity. With the maximum payload the table can accelerate up to 1g, has a maximum velocity of 97 cm/sec, a maximum peak to peak displacement of 25 cm, and operates in the frequency range of 0.1 to 50 Hz. A full flexible wall barrel and accompanying equipment are estimated to weigh on the order of 3500 kg.

Data is acquired using accelerometers, pressure sensors, load cells, displacement potentiometers, and LVDT's. Initial undrained strength of the soil is measured using T-bar pull out tests and top down shear wave velocity measurements. Accelerometer arrays are located throughout the soil column for time history measurements. LVDT's at the table based and displacement potentiometers along the side of the barrel track relative displacement. Pressure sensors are used to measure soil pressure at specific locations discussed below.

Figure 2. The (yellow) mixer on the left is used to mix the large volumes of model soil (composed of kaolinite, bentonite, fly ash, and water) for filling the barrel. The soil is filled to just below the top metal ring to avoid any interaction of the soil with the barrel frame. Soil mixing achieves a target water content of 110% to ensure proper model soil strength.

TESTING

A scale model basement wall, developed in Moss et al. (2011) is used to mimic both basement wall and retaining wall conditions (Figure 3). The single degree of freedom (SDOF) oscillator mimics the scaled period of a typical modern 3 to 5 story building. The model wall is equipped with an array of equally spaced tactile pressure sensors placed vertically along the center of the wall to measure the development of seismic earth pressures throughout the duration of the earthquake motion.

The soil column within the flexible wall barrel is instrumented with accelerometers at the soil surface free field, equivalent basement free field depth, the structural basement, and the top of the wall to best characterize the motion of the system during each seismic event. Clay is excavated to fully embed the scale model into the soil column. A suite of 14 earthquake motions (both horizontal azimuths) were selected to cover a wide range of seismic loading conditions.

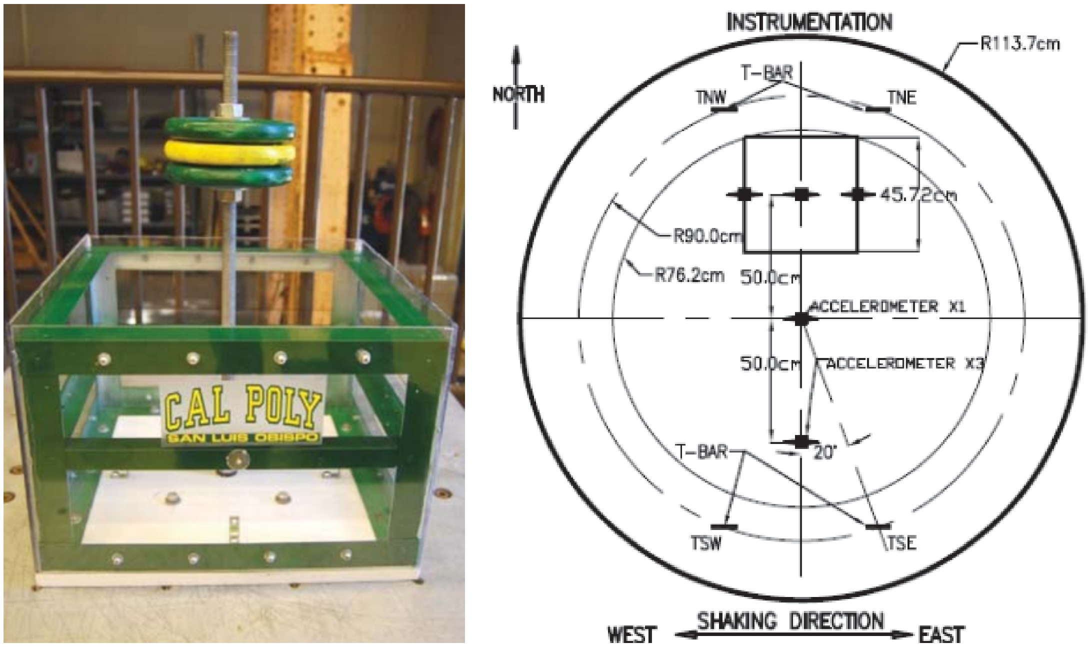

Figure 3. **Picture (left) shows the scale model basement and retaining wall. The foundation is 46cm square, and the wall for this configuration is 32cm tall. The single degree of freedom (SDOF) oscillator introduces soil-structure-interaction effects for basement wall conditions. Figure (right) shows plan view of the flexible wall barrel with accelerometer array layout, T-bar locations, and embedded model basement and retaining wall.**

The experimental testing is composed of two phases; modeling rigid walls and modeling flexible walls. In phase one of the study, the model wall is installed such that the retained soil would mimic static at-rest (K_o) condition typical of soils retained by rigid retaining walls or basement walls. In the second phase of the study, the model wall is installed such that the soil pressures developed on the wall were in an active state (K_a) typical of soils retained by flexible retaining walls. The tests presented in this paper were for an at-rest soil state, future tests will evaluate the active condition.

INVESTIGATIONS

For the initial tests the model SDOF basement wall was fully embedded and instrumented with two tactile pressures sensors that were located at 1/3H and 2/3H from the top of wall, where H is the wall height. The set up was then subjected to the suite of motions with both horizontal azimuths resulting in 28 shake table runs. During the tests the pressure sensor located at 2/3H did not read correctly so only the sensor located at 1/3H from top of wall is included in the results below.

Figure 4 shows the plots of the model soil acceleration and velocity time histories in response to the 1992 Cape Mendocino Earthquake (CPM-000) that was time step compressed for similitude, input as the shake table base motion, and propagated through the soil. Figure 5 shows the pressure time history on the wall at 1/3H from the top for the same motion. The sampling rate appears to be adequate for capturing the relative movement of the soil with respect to the wall. In these initial tests we found that the maximum pressure occurred at a slight delay from the maximum acceleration with a difference of roughly 0.1s. It is interesting to note that the velocity time history and the pressure time history have very similar time signatures which suggest that the momentum, of this wall arrangement with the SDOF oscillator installed, is the controlling loading.

Similitude analysis (Crosariol, 2010) dictates that pressure in the model tests are related to prototype pressures by the scaling factor (λ). In these tests the scaling factor is 10, therefore the prototype pressures are 10 times the model pressures. The pressure measurements from the shake table tests at 1/3H, shown in Figure 5, indicate a static model pressure of just over 1.3 kPa (slightly higher than at-rest conditions) that when converted to prototype scale is approximately 13 kPa. The seismic increment, which is the peak in Figure 5 minus the static or baseline earth pressure, was measured at 1.4 kPa or 14 kPa in prototype scale. This is the additional seismic earth pressure (ΔP_E) added to the static earth pressure (P) to give the total wall pressure during an earthquake (P_E). This suggests **an increase in pressure due seismic excitation, total over static (P_E/P), of slightly over 2.**

These model test results are then compared to M-O method recommendations by Lew et al. (2010). For clay soils there is a reduction applied to the M-O method to account for cohesion in the soil. The c-φ chart for a soil with a friction angle of 30 degrees was used, this based on consolidated undrained (CU) triaxial results of the prototype soil that gives φ~30 degrees (USACE, 2009). The CPM-000 motion presented here has a base input peak ground acceleration of 1.50g which in the clay profile produces +1.31 and -1.73g at the soil surface. When applying the M-O method with the clay recommendations (Anderson et al., 2008, and Lew et al., 2010) in order to get a similar seismic increment and factor increase in pressure to the shake table tests **1/3rd of the peak ground acceleration must be used for retraining wall acceleration (k_h)**. This reduction in peak ground acceleration for M-O method analysis can be compared to the typical reduction of 1/2 commonly used in practice (Lew et al., 2010).

Previous research by Al Atik and Sitar (2007) has shown that the M-O method tends to overestimates seismic earth pressures in sand experiments run in the centrifuge. The suite of shake table experiments planned for the coming months may elucidate exactly where seismic earth pressures in clay fall with respect to current prediction methods and ongoing centrifuge tests.

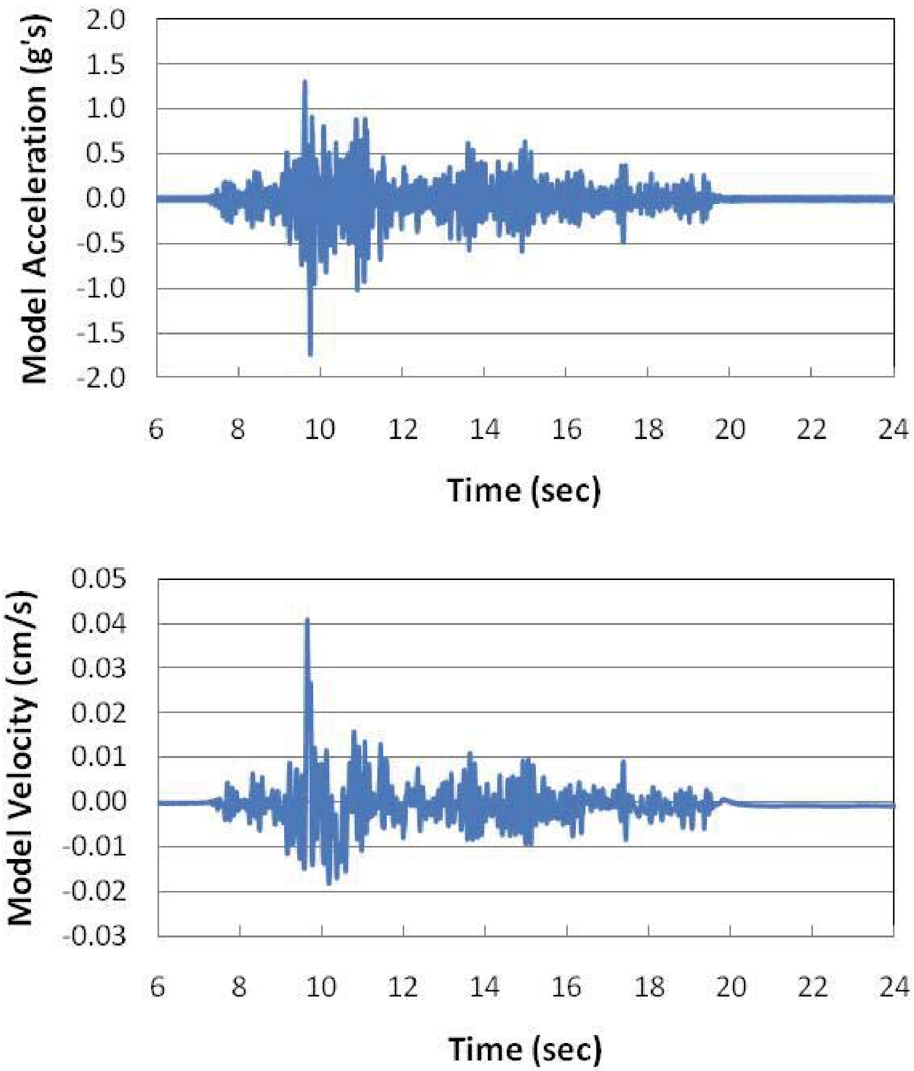

Figure 4. Model soil acceleration and velocity time histories in response to the table input earthquake motion CPM-000 (PGA=1.5g). Maximum horizontal acceleration occurs at t=9.61 s, the same time as the peak in velocity. For scale model similitude the time step is compressed ($\lambda^{0.5}$) to afford proper dynamic response on the shake table.

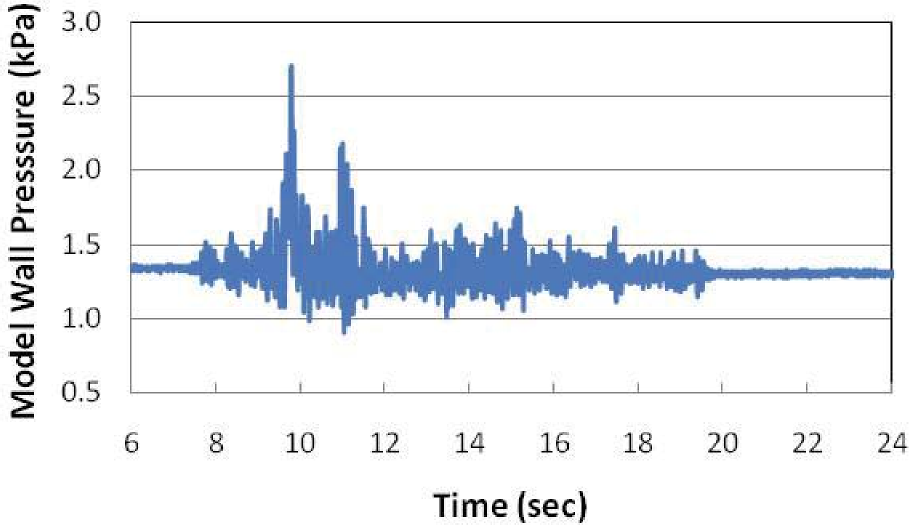

Figure 5. Model wall pressure time history in response to input table earthquake motion CPM-000 (PGA=1.5g). Maximum total scale model wall pressure, including the seismic increment, is P_{AE}=2.7 kPa at t=9.75 s. This is equivalent to 27 kPa in prototype scale as the scaling factor is λ=10 and pressure similitude is 1:λ.

FUTURE RESEARCH

Two rounds of subsequent tests are being carried out on both at-rest and active soil conditions to mimic rigid wall and flexible wall conditions. At least 6 pressure sensors will be used to capture the pressure magnitude and distribution along the model wall. These tests should provide a good basis for making informed decisions about how walls in clay behave when subjected to seismic ground motions.

For these tests it is assumed that because we are working with a saturated clay soil that the dynamic soil response will be wholly undrained with no volume change. A second assumption is that the flexibility of the wall during dynamic shaking in clay soil has an insignificant effect when compared to the starting initial horizontal stress conditions of active (K_a~0.33) or at-rest (K_o~0.5).

Wall height is a variable that has an impact on the seismic earth pressure. In these subsequent tests we will be modeling prototype wall heights from 3 to 5 m to encompass typical basement walls and medium height flexible walls. We will also be investigating how the wall and base adhesion influences the dynamic response, with care given to mimicking construction practices.

SUMMARY

This paper presents shake table tests evaluating seismic earth pressures for wall design in clay soil. The testing platform consists of a flexible wall barrel, 1-D shake table, and associated control and data acquisition equipment. A suite of motions were applied to the flexible wall barrel filled with scale model (YBM) clay soil that contained an embedded scale model single degree of freedom (SDOF) oscillator which mimicked basement wall conditions with inertial structural loading. Presented here are results when a large ground motion (CPM-000) with a base input peak ground acceleration (PGA) of 1.5g was applied. It was found that the static stress conditions are consistent with what would be anticipated in a normally consolidated clay soil for a 3m high prototype basement wall. The measured seismic earth pressures agreed with the Mononobe-Okabe method with a cohesion reduction when the peak ground acceleration used in the calculation (k_h) is 1/3rd of the measured peak ground surface accelerations. The time history of the wall pressure shows strong similarity to the velocity time history of the soil suggesting that momentum is the controlling loading for this type situation. Future tests are currently underway to comprehensively evaluate both flexible and rigid walls in clay soil.

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