**TPF SOLICITATION**

**TITLE**

Full-Scale Shake Table Tests of Seismic Performance of Reinforced Soil Walls

**BACKGROUND**

Earth retaining structures constitute a vital component of the civil infrastructure across the U.S. In high seismic risk zones, these structures are occasionally subjected to strong earthquakes that can threaten their integrity. Research is needed regarding seismic demand and performance of these structures under strong ground motion to improve existing design procedures. Experimental research of this type has traditionally been conducted by testing small physical models on actuator-driven shake tables or in geotechnical centrifuges. Small model tests give valuable information on general behavior but represent a compromise with respect to field structures because of low stress conditions (if 1-g), scaling effects, idealized backfill soil, idealized compaction conditions, and the need for non-standard structural elements, such as reinforcement and facing elements. What is needed for better understanding of the performance of reinforced soil walls during earthquakes is full-scale testing. For the first time, such testing is possible using new shake table equipment that be available at the University of California-San Diego (UCSD) starting in late 2012.

Current seismic design procedures available to state DOT’s (e.g., AASHTO) may be excessively conservative for many wall types, but also may be missing important design considerations important for good seismic wall performance. If current design models can be better understood or better design models can be developed that efficiently reduce conservatism while accurately capturing the seismic design issues that warrant greater attention, there is significant potential to reduce overall wall costs. This is important for existing use of MSE walls and future use of MSE abutments, which is a relatively new and cost-effective application for this technology.

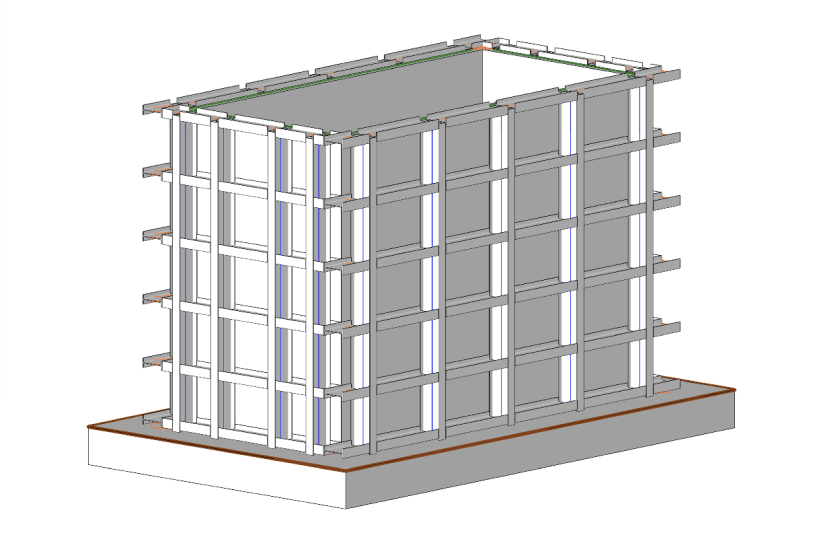
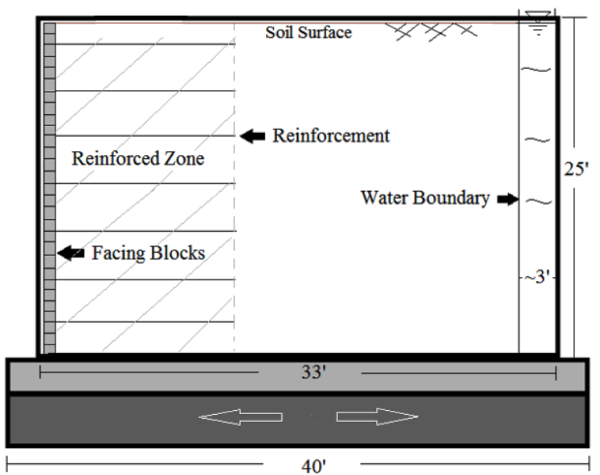
The new AASHTO seismic design requirements (moving from a 500 year to a 1000 year design earthquake) have increased the seismic demand on walls – the biggest impact is on the width of the wall design section now required to resist the seismic loading. Significant savings in wall costs could be achieved if the proposed research would allow for reduction of this width. Reducing the width of the wall section also directly reduces the amount of shoring and excavation needed to build a wall, resulting in significant additional savings. Increased demand on the internal components of these wall systems will also occur, and developing a more accurate methodology to estimate the internal stresses in walls is also needed.

A project, funded by the National Science Foundation (PI: Fox; total funding: $550,000), is currently underway at UCSD to build and test prototype full scale MSE walls (7 m, or 23 ft., in height) using UCSD’s Large High Performance Outdoor Shake Table (LHPOST). In addition, another project for Caltrans is in the final approval stage to use the same facility to conduct full-scale tests of “true” MSE bridge abutments (i.e., shallow foundation directly sitting on MSE wall). The purpose of this current pooled fund solicitation is to extend these projects by performing numerical studies and one or two additional full-scale MSE wall tests on the UCSD shake table. This work will complement the existing projects and allow us to develop a more complete understanding of the seismic behavior of reinforced soil walls without bridge abutment loads. Opportunities to use large testing facilities such as the LHPOST are rare, and the ability to take advantage of such facilities with the majority of funding covered by other agencies is even rarer. Thus, the cost of the proposed project is comparatively low because we can “piggyback” on other existing projects.

**OBJECTIVES**

The objective of this project is to perform numerical studies and use the LHPOST to investigate the dynamic performance of one or two full-scale (7 m) reinforced soil retaining walls constructed using realistic materials and methods. Considering that these walls will be substantially taller than for any similar previous research (by a factor of 2), a key focus of the proposed research will be on the influence of wall height on overall system response (i.e., stability/deformation) and the distribution of dynamic tensile forces (i.e., seismic demand) in the soil reinforcement. Other focus areas will include dynamic earth pressure on facing elements, effects of dynamic loading on soil-reinforcement stress transfer mechanisms, and permanent deformations after dynamic loading.

The tests will be conducted using a unique large soil confinement box (LSCB) that is currently under construction as part of a recently funded NSF grant. Figure 1 shows a 3D view of the LSCB after construction and a cross section view of a reinforced soil retaining wall specimen inside the LSCB. The LSCB will be constructed of steel and concrete and will allow for dynamic testing of wall specimens with maximum dimensions of 6 m × 12 m × 7 m high. The scale of these tests will permit wall construction using realistic soil types, compaction methods, and structural elements. The box will also have a unique design that permits different boundary conditions at the rear of the soil mass, including a water-filled bladder or geofoam layer.

(a) (b)

**Figure 1. Large soil confinement box on LHPOST: a) empty box and, b) cross section of MSE wall specimen.**

**SCOPE OF WORK**

The project will consist of dynamic testing of one or two MSE walls, each approximately 7 m in height. The specific types of walls to be tested will be established in discussion with the TAC (Technical Advisory Committee) for the study and representatives from each of the funding organizations (e.g., state DOTs). The wall specimens will be constructed using realistic soil types (e.g., well graded granular material with some fines), compaction methods (e.g., rolled soil lifts), reinforcement (e.g., geogrid or steel strips) and facing elements (e.g., modular blocks or precast panels). Each wall will be shaken at several heights during construction (e.g., 2 m, 6 m, 10 m) to assess the effect of wall height on dynamic response. Tests on a given wall at intermediate stages will be conducted using only moderate excitation. Once construction is completed for each wall (i.e., full height), specifications for the LHPOST indicate that peak accelerations of approximately 0.8*g* can be achieved.

The LHPOST is located at the Englekirk Structural Engineering Center of the Powell Structural Research Laboratories at UCSD. The LHPOST is the second largest shake table and the only outdoor shake table worldwide. The table measures 7.6 m × 12.2 m and permits simulation of large earthquake ground motions. In its current configuration, the LHPOST has a stroke of ±0.75 m, a peak horizontal velocity of 1.8 m/s, a horizontal force capacity of 6.8 MN, and a vertical payload capacity of 20 MN. The testing frequency range is 0-33 Hz. Although designed for full 6 degree-of-freedom (DOF) capability, the LHPOST currently has uniaxial (horizontal) motion capability. Work is currently underway to upgrade the table with vertical motion capability.

The MSE wall specimens will be instrumented with sensors, including accelerometers, strain gages on reinforcement, earth pressure cells, displacement transducers and possibly shape acceleration arrays (SAAs). SAAs (Abdoun *et al.* 2005) are a rope-like array of sensors and microprocessors that fits into a small (27 mm ID) casing. If the budget permits, SAAs will be installed and grouted in vertical drilled holes after backfill construction (e.g., near facing, at middle of reinforced zone, at back of reinforced zone) and will measure the change of casing shape similar to an inclinometer. The advantage of the SAAs is that they can measure lateral displacements in real time during dynamic loading. All other instrumentation is currently available through NEES@UCSD at no cost to the project. Sensors will be placed within wall specimens as needed during construction. Strain gages on reinforcement (geogrid, soil nails) will be load-calibrated to the fullest possible extent to reduce measurement variability. Total pressure cells suitable for dynamic pressure measurement will be placed behind the facing, similar to methods previously used by Dr. Elgamal (Wilson and Elgamal 2008, 2009a,b,c, 2010). Video footage of the top surface and front face will also be collected during testing. Similar instrumentation methods were used in a full-scale study of the static stability of a 55 ft. (17 m) high retaining wall conducted by Dr. Fox (Runser *et al.* 2001). Excitation for the full-scale walls will consist of a range of input motions including low amplitude frequency sweeps and records from one or more large earthquakes.

In addition to the experimental work, numerical studies will be conducted on dynamic performance of MSE walls using the geotechnical analysis software FLAC, which has a long track record of success for soil-structure interaction problems and is available to the project at no cost. Investigated variables are expected to include wall height, facing element types, reinforcement types and layout, soil backfill properties, and shaking time-histories. FLACTM (Fast Lagrangian Analysis of Continua) is a leading computer analysis package for deformation and stability of geomaterials developed and supported by the Itasca Consulting Group, Inc. (*www.itascacg.com*). FLAC has been selected for this research over other available platforms because of its availability to the project and its successful record of use for MSE structures (Bathurst and Hatami 1998; Hatami and Bathurst 2000; Zarnani and Bathurst 2009; Huang et al. 2010). In addition,

* the lagrangian formulation in FLAC can accommodate large displacements and strains, including non-linear material behavior, yield, or failure over a large area, up to total collapse;
* FLAC has an interface modeling option that includes Coulomb sliding, tensile strength and separation, and normal and shear stiffness – which will be advantageous for the simulation of settlement- and/or seismically-induced deformations of MSE abutments;
* FLAC has an extensive array of constitutive models for geomaterials, including hyperbolic models for granular materials and equivalent linear models for dynamic response;
* FLAC allows for user-developed constitutive models through the FISHTM programming language; and
* the registered user base for FLACTM is now over 2500 and, as such, a large community of researchers and practitioners can benefit from the methods developed for this project.

Results from FLAC analyses will be used to design the experimental conditions for the MSE wall tests to maximum advantage.

**SPONSORING STATE/AGENCY –** Washington State Department of Transportation (WSDOT).

**SPONSORING AGENCY CONTACT** – Tony Allen, [allent@wsdot.wa.gov](mailto:allent@wsdot.wa.gov), 360-709-5450

**LEAD STATE/AGENCY -** Washington State Department of Transportation (WSDOT).

**LEAD AGENCY CONTACT** – Tony Allen, [allent@wsdot.wa.gov](mailto:allent@wsdot.wa.gov), 360-709-5450

**COMMITMENTS REQUIRED** – $150,000

**DURATION** – 36 months

**MINIMUM STATE COMMITMENT** (in dollars) – $20,000

**START YEAR –** March 1, 2013

**DATE SOLICITATION EXPIRES** – December 31, 2012

**ATTACHMENTS** – Additional background information regarding previous work in this area is as follows:

**Seismically-Induced Damage Mechanisms in Reinforced Soil Walls**

In the 1989 Loma Prieta earthquake, retaining wall performance was generally considered satisfactory (Felio *et al.* 1990; Kutter *et al.* 1990; Eliahu and Watt 1991; Collin *et al.* 1992; Reinforced Earth Co. 1994; Vucetic *et al.* 1998). In the 1994 Northridge earthquake, only one MSE wall was badly damaged (Frankenberger *et al.* 1996; Sitar *et al.* 1997). As for geogrid reinforced walls, some signs of distress, in the form of face bulging, settling, and tension cracks in the fill behind the wall were observed (Sandri 1994).

In the 1995 Kobe earthquake, damaged MSE structures (Kobayashi *et al.* 1996; Tatsuoka *et al.* 1996a; Tatsuoka *et al.* 1996b) included a railway embankment designed with a seismic coefficient of 0.15 (actual PGA was 0.8*g*). Seven soil nailed walls experienced significant movement at the top of the wall (Tatsuoka 1995). A geogrid-reinforced wall with a height of 5.3 m and relatively short reinforcement moved outward by 0.3 m (Tatsuoka 1995; Tatsuoka *et al.* 1996a; Tatsuoka *et al.* 1996b; Tatsuoka *et al.* 1998).

In the 1999 Chi-Chi, Taiwan earthquake, damage was reported in geogrid-reinforced walls with modular facing blocks. A significant number of failures were observed (Chen et al 2000; Huang 2000; Ling *et al.* 2001; Ling and Leshchinsky 2005). The failure modes observed included global stability failures, wall bulging and cracking, and failure of the connection between the reinforcement and facing blocks. Many failures were noted in relatively short walls, with heights under 5 m. The required seismic design coefficient for these structures was 0.115, while PGA was about 0.4*g*. Typical maximum bulging deformations occurred in the lower 1/3 of the wall profile.

In the 2000 Nisqually earthquake (Kramer *et al.* 2001), a 4.5 m high wall with 3.5 m long reinforcement and modular-block concrete located 27 km from the epicenter collapsed (PGA at the location was about 0.15*g*). This particular wall had suffered construction problems due to soft foundation soils, an issue which might have contributed to this poor performance. Another wall, 30 km from the epicenter remained intact, but the soil behind it experienced a wedge-type failure (under an estimated PGA of 0.07*g*). Lateral displacements of 25 cm and vertical displacements of 2 to 3 cm were recorded. This wall was 5.5 m high, with reinforcement lengths of 2.8 m, giving a length-to-height ratio of 0.5 (below the typically recommended ratio of 0.7). An important aspect of this wall’s performance is that it remained intact, moving as a unit and causing distress in the retained backfill (behind the reinforced zone).

As such, it can be generally concluded that reinforced soil walls that have experienced low to moderate levels of shaking have performed satisfactorily, as also observed during the recent 2010 Chile Earthquake (Bray and Frost 2010). High levels of earthquake excitation may cause visible signs of distress at various locations within and behind the reinforced zone.

Overall, however, there have been very few wall collapses, and those that did collapse were limited to old concrete walls and on occasion a modular block geogrid wall. As far as we know, collapses have occurred only if the walls were already in distress before the earthquake, such as due to using clay backfill, lack of drainage, etc. It is more surprising that many walls have performed very well in big earthquakes that were really not designed for significant seismic loading. Yet available design procedures do not indicate this good performance. Data from the proposed full-scale tests will help us to address this important question so that we can move forward with more realistic design methods. More realistic methods will help WSDOT and others to better invest tax dollars in more seismically robust wall designs only when really needed, rather than apply overly conservative designs to all walls due to the current lack of knowledge in this area.

**Physical Model Testing**

As a result of the above experience in recent earthquakes, current design practice for reinforced soil walls remains under scrutiny (Reinforced Earth Co. 1990, 1991, 1994; Eliahu and Watt 1991; Collin *et al.* 1992; Sandri 1994; Stewart *et al.* 1994; Sitar *et al.* 1995; Tatsuoka *et al.* 1996b; Ling *et al.* 1997; Ling *et al.* 2001, 2003a). In general, field reports indicate that reinforced soil walls may deform under seismic loading and that complete failures are rare. Face bulging, and facing element spalling and cracking are the most commonly observed problems. In many cases, this poor performance appears to be associated with local failures of mechanical or frictional connections between reinforcement and facing elements. As such, observed failure modes are mainly: i)generic MSE structures (whether reinforced with geogrids or metallic strips) may experience bulging in their lower sections, ii) backfill deformation behind the reinforced zone may occur with the reinforced soil wall moving as a unit without collapsing, and iii) the limited data from soil nail walls indicates that the maximum deflections tend to occur in the upper sections of the structure.

While post-earthquake field studies have provided valuable insight into seismic wall performance, physical model testing remains a vital tool for the investigation of dynamic wall/soil behavior. Such testing has been performed on small model retaining walls/components in laboratory and pseudo-static tilt-up tests (Vagneron and Adams 1972; Koseki *et al.* 1998; El-Emam *et al.* 2007; Huang *et al.* 2008; Ling *et al.* 2008), on 1-*g* shaking tables (Richardson and Lee 1975; Bathurst *et al.* 1996; Matsuo *et al.* 1998; Ling *et al.* 2005; Krishna and Latha 2007), and in dynamic centrifuge tests (Jaber et al. 1990; Casey *et al.* 1991; Zornberg *et al.* 1995; Sakaguchi 1996; Howard *et al.* 1998; Nova-Roessig and Sitar 1998, 2006; Nova-Roessig 1999). Small model tests give valuable information on general behavior but are limited by low stress conditions (1-*g* tests), scaling effects for soil stiffness and strength (centrifuge tests), the size and number of sensors, idealized backfill soil and compaction conditions, and the need for non-standard facing and reinforcing elements. Testing of full- and half-scale walls has been very limited due to the high weight (i.e., payload) of the system.

Using the centrifuge, Nova-Roessig and Sitar (2006) found that previous tests using scaled shake table or blast-loading models frequently displayed failure modes that are not observed in the field. This was attributed to the use of reinforcement with low tensile or soil-friction strengths, and the use of backfill material that was stiffer than the prototypes. It was found that soil deformation may occur at relatively low accelerations, with significant vertical and lateral movement observed during strong shaking. Reinforcement length and spacing, and backfill density, were found to have a significant effect on performance. Other notable studies (Siddharthan *et al.* 2004; Woodruff 2003) also showed length of reinforcement to be critical to wall performance; short reinforcement (i.e., reinforcement length less than about 0.5 wall height) was prone to overturning failure, in which the failure plane did not cross any lines of reinforcement. The maximum wall-face deformation was consistently found to be in the lower third of the wall.

Centrifuge testing dealing specifically with soil-nailed walls was performed by Vucetic *et al.* (1993, 1996, 1998) and Zhang *et al.* (2001); the results showed good agreement with observed soil-nail wall performance. Nail length and spacing were important parameters, influencing both the strength and geometry of the failure surface. The work done by Vucetic *et al.* (1993, 1996, 1998) included seismic excitation (Tufenkjian *et al.* 1991; Tufenkjian and Vucetic 1992, 1993).

In terms of full-scale testing, Richardson *et al.* (1977) built a single 6.1 m reinforced soil wall and subjected it to blast loading. Murata *et al.* (1994) tested half-scale (2.5 m) reinforced soil gabion walls on a laboratory shaking table with a maximum acceleration of 0.5*g*. These tests showed amplification of the base motion ranging from 1.5 to 2 at the crest and maximum seismic compression settlements of 30 mm. Large-scale tests were also reported by Ling *et al.* (2003b, 2005) for three 2.8 m high modular block reinforced soil walls for accelerations up to 0.86*g*. Test results indicated that the walls deformed very little and with little horizontal acceleration amplification. Interestingly, part of the lateral deflection, earth pressure and tensile force in the reinforcement were recovered when shaking ceased. The measured amplification ratio of 1.35 indicated that the particular wall system performed better than conventional walls that had been tested for earthquake loading.

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**COMMENTS** – Since the proposed project is intended to be a continuation of a currently funded NSF project, including use of the same equipment, the project investigators are the same as for the current project:

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