Seismic Study of Geosynthetic-Reinforced Slopes

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PEER Summer Internship Report
University of Washington
Summer 1998

ACKNOWLEDGEMENT

First, I want to express my appreciation to the National Science Foundation for funding the Undergraduate Summer Internship Program with the Pacific Earthquake Engineering Research Center (PEER) at the University of Washington. I also want to thank the President of the Polytechnic University and the members of the American Association of Civil Engineers (ASCE) for their help in making this internship experience possible. Most of all, thanks to Prof. Omaira Collazos and Prof. Pedro Arduino for their support, guidance, and advice.

ABSTRACT

This report was done as part of an internship program sponsored by the NSF to learn and get involved in an extensive research at the University of Washington. The research is related to issues associated to the design of reinforced slopes and the dynamics of slope stability. The report would be directed to what I have worked on and learned during this summer internship.

The main objectives of this research were:

1- *to increase the fundamental understanding of the seismic behavior of goesynthetic-reinforced slopes; and*
2- *to develop a realistic displacement-based analytical model for practical seismic design of geosynthetic-reinforced structures.*

Meeting these research goals will lead to a much better understanding of how geosynthetic-reinforced slopes perform under seismic loading conditions. This will allow modifications of extremely conservative current design methods.

The following paper focuses on the shaking table (the physical model phase of the research project) investigation that is being conducted at the University of Washington on the capabilities of possible analytical methods currently used for the design of reinforced slopes. First, a summary of shaking table studies is presented as an overview of past tests. Then, a description of the equipment, the construction, as well as the results obtained in the latest tests of the shaking table test are included. Finally, a conclusion of the last shaking table test is presented with recommendations for further tests.

SINOPSIS

El siguiente informe forma parte de un programa de internado auspiciado por la NSF con el fin de cooperar en una extensa investigación llevada a cabo en la Universidad de Washington y aprender de ella. La investigación trata sobre temas relacionados con el diseño de pendientes reforzadas y la estabilidad dinámica de estas pendientes. El informe se dirige en torno a lo que trabajé y aprendí durante mi participación en el programa de internado.

Los objetivos principales de la investigación fueron:

1- *aumentar el entendimiento del comportamiento sísmico de las pendientes reforzadas con geosintéticos; y*
2- *desarrollar modelos analíticos realistas, basados en desplazamientos, para hacer diseños sísmicos prácticos de estructuras reforzadas con geosintéticos.*

El conseguir estas metas permitirá entender mejor cómo actúan las pendientes reforzadas bajo la condición de carga dinámica, lo que a su vez permitirá modificar los métodos de diseño actuales, los cuales son extremadamente conservadores.

El siguiente informe se enfoca en la investigación de la mesa agitadora ("shaking table"), la fase del modelo físico, la cual se está llevando a cabo en la Universidad de Washington sobre las posibilidad de desarrollar métodos analíticos para el diseño de pendientes reforzadas. Primero, se presentará un resumen de pasados estudios en mesas agitadoras. Luego, se incluirá la descripción del equipo, su construcción, al igual que resultados obtenidos de las pruebas más recientes. Finalmente, se presentará una conclusión de las últimas pruebas incluyendo recomendaciones para futuras pruebas.

I- INTRODUCTION

Present design practice and building codes limit the steepness of reinforced soil slopes to 2H:1V. Rapid growth in many metropolitan areas has reduced buildable land and greatly increases the cost of property at sites with steep terrain. Construction of steep slopes (slopes greater than 2:1) would increase available land as well as decrease property costs. An increasing number of geosynthetic-reinforced slopes have been constructed throughout the world, including many in seismically active areas. Unfortunately, little research has been done that could support the use of steep geosynthetic-reinforced slopes in seismically active areas. This lack of understanding has led to the development of very conservative design procedures and, in some cases, to limitations on the steepness of slopes that do not fully recognize the benefitial effects of slope reinforcement.

Current design procedures for reinforced slopes consist merely of static analysis, with the possible inclusion of a pseudo-static force applied to account for seismic loading. As a result, a factor of safety against instability is obtained. This analysis cannot predict the magnitude of displacement, which will determine the serviceability of a slope after a seismic event. Therefore, the current design methods for reinforced slopes provide no insight into the behavior that really governs in a reinforced slope after a seismic event.

For the purpose of overcoming this limited understanding of how geosynthetic-reinforced slopes perform under seismic loading conditions the National Science Foundation (NSF) has recently sponsored a research project which involves three phases: (a) centrifuge model tests, (b) physical model tests – using a shaking table; and (c) an analytical and numerical model test, using finite element computer algorithms.

II- DESCRIPTION OF SHAKING TABLE TEST

The shaking table test is a model test for seismic studies where a reduced-scale model is constructed on top of a shaking table and subjected to a dynamic loading. One of the advantages of the shaking table tests is that they are relatively easy to perform. The construction of the shaking table model is not very time consuming in comparison with the duration of the prototype construction. An important advantage of the test is its ability to model most of the prototype conditions, in view of how close the model really is from the prototype. In the shaking table test the stresses that are developed inside the slope can be determined without the need of modeling. Past shaking table studies have helped to identify important performance features of reinforced soil structures under dynamic loading. For example most investigators have noted amplification of base input acceleration over the height of structures particularly at the top of the structure. The disadvantages that are mainly recognized for this test are:

1- Similitude

One of the principal disadvantages is related to the problem of similitude between reduced-scale models and equivalent prototype scale systems. Of particular concern is the difficulty of 1g models to scale nonlinear soil strength and stress-strain properties that vary with confining pressure. A consequence of these difficulties is that the failure mechanism observed in the reduced-scale model may be different from those observed at the prototype scale. Nevertheless the variance of these differences is not too large. Theoretically, these scaling difficulties identified for 1g shaking table tests can be overcome using the centrifuge testing.

2- Boundary Effects

The boundary effects are divided into backwall and sidewall effects; and both alter the true conditions that a reinforced slope has in the field. When the waves carried by the soil strikes the rigid boundary (the backwall), a reflection of the wave with the same amplitude and polarity will result, consequently imparting energy in the slope that would not naturally occur. Additional displacements and density changes can result from the additional energy and the inability of the soil adjacent to the rigid wall to deform as it would do in the free-field. The sidewalls provide a frictional resistance at the interface that tends to strengthen the overall slope and may induce error in measurements and alter modes of failure. Plastic sheeting was used along the sides of the box to reduce friction to a minimum.

The first use of the shaking table test to investigate the seismic stability of geosynthetic-reinforced steep slopes was in 1988. Table 1 summarizes the studies that have been performed

Table 1: Summary of shaking table studies

Reference	Model Details	Observed behavior and implications to design and analysis
Koga et al. 1988; Koga and Whashington 1992	1-1.8 m height models with vertical and inclined slopes at 1/7scale. Non woven geotextile, plastic nets and steel bars with sandy silt backfill.	Deformation decreased with: (1) increasing reinforcement stiffness (2) increasing density (3) decreasing face slope angle. Failure volumes were shallower for reinforced structures. Relative reduction in deformation of reinforced structures increased with steepness of the face, compared to unreinforced structures. Circular slip method agrees well with experimental results except for steep face models.
Murata et al. 1994	2.5m high ½ scale model walls with gabion/rigid concrete panel walls. Geogrid with dry sand backfill. Horizontal shaking using sinusoidal and scale earthquake record. Base accelerations up to 0.5g at 3.4 Hz.	Increase in reinforcement forces due to shaking was very small. Reinforcement loads increased toward the front of the wall. The behavior of reinforced and unreinforced zones due to acceleration amplifications was similar. Sinusoidal base input resulted in greater deformations than scaled earthquake record. The reinforced zone behaved as monolithic body. Rigid facing adds to wall seismic resistance.
Sugimoto et al.1994; Telekes et al. 1994	1.5 m high model embarkment. Goegrid reinforcement with sand backfill. Model scale 1/6 and 1/9. Sinusoidal and scale earthquake record. Base acceleration up to 0.5g at 40 Hz.	Reinforced models more stable than unreinforced. Proposed similitude rules for small and large strain deformation modelling. Largest amplification recorded at crest of models. Reinforced forces increased linearly with acceleration up to start of failure. Failure mechanism difficult to predict using proposed scaling rules. Scale effects due to vertical stress and apparent cohesion of backfill soil influenced the relative performance of steep faced and shallow faced models.
Budhu and Hallolum 1994	0.72 m high model wall with wrap- around facing. Geotextile with dry sand backfill. Base acceleration in increments of 0.05g at 3Hz.	Sliding progressed with increasing acceleration from the top geotextile/sand interface to the bottom layer. No consistent decreasing trend of critical accelerations was observed with increasing spacing ratio. Critical acceleration proportional to the soil/geotextile interface friction value.
Sakaguchi et al. 1992; Sakaguchi 1996	1.5 m high model walls. One wrap around and 4 unreinforced rigid concrete panel walls. Geogrid with dry sand backfill. Sinusoidal loading with base acceleration up 0.72g at 4 Hz.	Wrap-around wall behaved as a rigid body and failed at a higher acceleration than unreinforced structures. However, at smaller accelerations the displacements of the unreinforced structures were fewer. It was concluded that more rigid light-weight modular block facings may be effective in reducing reinforcement loads.
McAlroy 1996	1.22 m height of model. Slopes of 63° were reinforced with a light-weight nonwoven textile. Wrapped face construction was used. Sinusoidal loading with base input motions of 6 Hz. The soil use was a clean, fine sand.	With increase reinforcement length, the yield acceleration appeared to decrease at mid-height of the slope in the center of the sliding mass. With decreasing spacing of the reinforcement, yield acceleration increased at mid-height of the slope in the center of the sliding mass. With decreasing spacing of the reinforcement, displacements per cycle decreased for a given value of the ratio of yield acceleration to maximum acceleration. Increased static factor of safety for the reinforced slopes, increases yield accelerations at mid-height of the slope in the center of the sliding mass. Strains developed in the reinforcement during shaking were greater near the middle of the reinforcement and decreased near the slope face. The failure plane originated at the top of the slope, at a distance approximately equal to the embedment length from the slope crest.
Perez 1998	1.22 m height of model. Slopes of 60° were reinforced with a nonwoven textile. Wrapped face construction was used. Sinusoidal loading with base input motions at 5 Hz with base accelerations up to 1.0g. The soil use was a clean, fine sand.	Prepared by December of 1998.

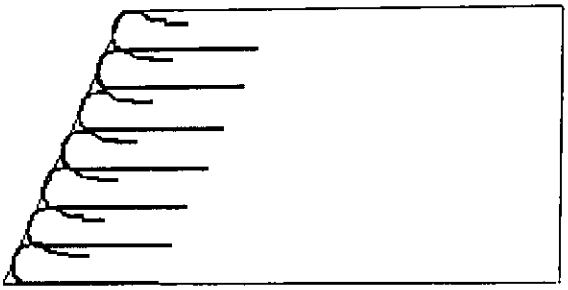

Figure 1: Model of a reinforced steep slope using wrap-around geosynthetic facing

on seismic stability of reinforced slopes with the use of the shaking table test until the present. The shaking table portion of the "NSF Steep Slopes" project is being performed at the University of Washington and is on its second phase of data collection. James McElroy completed the first phase in the fall of 1997. During his research a series of ten model reinforced slopes was tested. The second phase is being conducted by Adam Pérez and will be completed by the end of 1998. So far, a total of eleven slopes have been built under Pérez's direction. Construction of his latest slopes and data from these slopes will be discussed in this section.

Section III presents a description of the equipment, instruments and general materials that are involved in the shaking table tests.

III- DESCRIPTION OF THE EQUIPMENT

1- Shaking table

The University of Washington shaking table is 16 ft long by 8 ft wide and weighs approximately 6 tons. A soil box with internal dimensions of 8 ft* 6 ft* 4 ft (length * width * height) is mounted on the shaking table. The geosynthetic-reinforced model slopes were constructed in this box. The slope models were approximately 4-ft high and were intended to be scaled versions of 20 ft reinforced slopes to allow for comparison with the FLAC and centrifuge models.

2- Instrumentation

a- Potentiometers

Potentiometers (Model M1326-4) were used throughout the entire testing program to measure displacements of the slope face and backslope during dynamic loading. The output signal from each potentiometer ranged from 0.0 V for no displacement to 10.0 V for full scale displacement, and required no conditioning.

b- Accelerometers

Strain gage accelerometers (MODEL JTF/3629-05) were used for acceleration measurements in the reinforcement from double integration of the time histories, and for base input motion measurements in the shaking table. The accelerometers were capable of measuring accelerations of −10 g to +10 g over a wide range of frequencies.

c- Telltales

Telltales are used in each slope to better illustrate the mode of failure and the specific location of displacements within each slope. Three different types of telltales were used:

1) Solders – Two 122 cm long sections of soft wire solder were placed parallel to and on opposite sides of the centerline of the slope, each 30.5 cm from the centerline. The solders indicate the location of the failure.
2) Golf balls – Hollow, plastic "practice" golf balls were placed behind the textile along the centerline of the slope at 50 mm intervals between each ball. The balls were light weight and a series of holes allowed them to be easily filled with sand. This keeps the balls from moving through the sand during shaking (a problem discovered in preliminary tests using glass marbles). The balls indicated the location of the failure plane as well and showed how much movement occurred within the slope.
3) Soil displacement markers - One line of eight plastic tacks, placed on every layer. The line is parallel to the centerline of the slope, 30.5 cm from the centerline. This telltale is a new instrumentation that will be used for the remaining tests. These markers will allow a better estimation of the line of

failure and the horizontal and vertical displacements after the shaking.

3- Compactor

The compactor consists of a vibratory motor mounted on a 4.8 mm thick steel plate, weighing 18.5 kg. The edges of the plate were turned up and welded to reduce the tendency of the compactor to dig into the sand while vibrating.

4- Soil parameters

The soil selected for this research was also used in the centrifuge portion of the study by Anderson (1997). It was a clean, fine sand designated as a 4060 (60% retained on the No. 40 sieve). A series of laboratory tests were conducted in accordance with ASTM standards, the laboratory results are shown in table 2:

Table 2:Laboratory results for Unimin 4060 sand

USCS Soil Classification	SP
$\rho_{d,max}$	1.52 (g/cm^3)
$\rho_{d,min}$	1.28 (g/cm^3)
$\rho_d (D_r = 91\%)$	1.50 (g/cm^3)
e_{max}	1.109
e_{min}	0.776
ϕ	42°

Triaxial compression tests were conducted at different confining pressures. Each sample was compacted to a relative density of 91 % to represent the conditions for each slope during the model testing. For a non-cohesive soil, such as the sand used in the model slope construction, the slope of the Mohr failure envelope represents the angle of internal friction for the soil. After repeatable results were obtained from the triaxial and direct shear tests of this research, an angle of internal friction of 42° was chosen as a representative measure of the angle of internal friction for the 4060 sand.

5- Selection of Model Reinforcement

A preliminary selection of the reinforcement to be used in the model testing was made by performing Wide Width Tensile Tests (ASTM D4595). In this second phase of the shaking table tests a geotextile stronger than the geotextile chosen in McElroy's shaking table models was sought. A non-woven heat bonded geotextile with a reinforced strength of 4.9 lb/in was chosen. This geotextile was used for the last 7 tests. A woven geotextile was used in the first 4 tests but this was changed because the woven geotextile did not simulate what was being modeled and it did not match with the textiles used in the centrifuge tests. A woven reinforcement in the model represented a geo-grid in true scale, and this is not what was being modeled.

IV- CONSTRUCTION OF THE MODEL TESTS

Construction of each layer requires careful placement of the textile to ensure that the reinforced length is correct. Accelerometers were bonded in the reinforced layer number 3, 6 and 9 of the total of 10 that were present in the slope model. An additional accelerometer was mounted rigidly to the shaking table to monitor input motions. Telltales were then placed at specific locations within the slope. With the exception of the first layer, two solders were placed in each layer (parallel to the centerline of the slope, each one at 1 ft off the centerline). Six golf balls were placed along the centerline with a spacing of two inches from each other, on layers 3, 6, and 9. The elevation and the location of the solders as well as the golf balls were carefully measured during installation.

After the textile and instrumentation were properly positioned, sand was placed with the aid of a grain elevator. Sand from the chute was directed into buckets and then spread throughout the box until the desired volume of soil prior to compaction was achieved. In order to provide a specific amount of soil for each layer, a constant monitoring of the weight of sand being added was done, until the required weight was reached. Once a sand layer was placed, a compaction time corresponding to a relative density of 91% to 92% was used. Because a uniform density had to be reached, a specific time of compaction was needed for each layer and by extension, a monitoring of the usage time of the compacting machine was done. Care was taken when stepping on the sand to avoid additional compaction. The soil box was stepped only when the sand was going to be compacted. Boards were placed over the sand to spread out the weight of the worker and to keep the worker from disturbing the sand already at the desired density or compaction.

The potentiometers were mounted on a frame, which was placed and bulted onto the soil box. The potentiometers were placed along the face of the slope to measure horizontal displacements at the centers of layers 3, 6, and 9. Another potentiometer was placed against the table to monitor the displacement of the table. A temporary facing support form was used to maintain the desired slope angle of the textile layer being constructed. It consists of steel channels beside the face of the slope where boards are added as each layer of soil is constructed. This facing system allows for an easy removal prior to shaking. Finally, after positioning the slope crest potentiometers, the facing support system was removed.

The shaking of the slope attempts to model a unidirectional sinusoidal motion in the direction of the face of the slope (back and forth). All of the slopes were shaken at 5 Hz. The shaking was stopped when the horizontal displacement of the face of the slope was approximately 5 cm near the top of the soil. The reason for limiting displacement was to avoid catastrophic failure of the slope. This would possibly damage the instruments and would not allow us to monitor the movements on the inside of the slopes through the use of telltales, which had been placed at specific locations during construction.

Physical measurements were made after shaking. Movement of the slope crest and backslope were also carefully documented. After exterior slope measurements were completed, the slope was carefully excavated. Reinforcement layers with telltales were cautiously excavated to minimize disturbance that could alter the true deformations. Measurements of the deformation and displacement of the solder were recorded as well as the vertical and horizontal displacements of the golf balls.

V- RESULTS

The total vertical displacement obtained at the top of the slope after the shaking occurred was approximately 2.6 in. Plots of the line of failure of the reinforced slope were attained using the collected measurements of displacements and deformations of the solders and the golf balls after the slope failed. See appendix for plots that resulted from shaking table tests of the non-woven heat bonded textile, with 12 in and 10 in of embedment length.

Observations:

- After plotting the experimental results, and from the observations of the slope after it failed, we may conclude that the mode of failure performed by the reinforced slope model of the last two tests was of the "pullout" type, meaning that it occurred behind and under the reinforced area. See Figure 2.

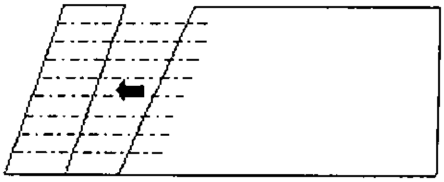

***Figure 2:** Pullout failure*

- For this specific situation the geotextile can be considered strong because it did not break or showed signs that it was soon going to break.

ADDITIONAL ISSUES

The following issues are related to the shaking table tests performed at the University of Washington under the direction of Adam Pérez.

- The first four models were done with a woven geotextile that had to be changed because it did not model what it was supposed to represent in a bigger scale, and it was not equivalent to the model used in the centrifuge tests for future correlation analysis.
- The first four tests had too many variables, for example the angle of slope and the number of layers. This led to inconclusive results.
- The second textile chosen, the non-woven heat bonded was too strong for the model of the shaking table.
- A thin sand layer that was being placed prior to the placement of the first textile layer was eliminated because it made the slope fail in an unwanted mode of failure.
- Excessive settlements in the slope at the backwall occurred while shaking because of the boundary condition problem of the backwall which performs a bouncing behavior that it is not realistic.
- Little information of displacements was obtained from the tests, more information is needed.

CHANGES FOR FURTHER TESTS

- A change of geosynthetic for a different type of non-woven heat bonded textile was decided for future tests. The reason for this change is to evaluate the performance of textile of intermediate strength in comparison with the textile used by McElroy (very weak) and the textile used in the last shaking table tests by Pérez with a non-woven textile (a strong geosynthetic).

- New instrumentation (telltales) will be added to the next test. These telltales are called soil displacement markers and consist of a line of plastic markers parallel to the centerline, they will show more efficiently the failure surface line and, at the same time, show the vertical and horizontal displacement after failure occurs.
- The solders and the golf balls were removed from the model.

VI- CONCLUSIONS

Using geosynthetics as reinforcement can allow the flexibility of using steeper slopes than the 2H:1V slope in seismically active areas. Even though the shaking table test method has some limitations such as the boundary conditions effect and the similitude problem, the test is providing a better understanding of the internal behavior of a steep reinforced slope under a dynamic loading condition. The knowledge and understanding that this research can provide may result in new, less conservative and more economical designing methods. At the same time, the use of geosynthetic reinforcement inside the geotechnical engineering seismic field will be expanded.

The last two tests of the shaking table performed at the University of Washington failed by pullout failure. This tells us that the reinforcement length is too short or that the reinforcement strength is too strong. No strains were found in the reinforcement; for that reason it is almost certain that the reinforcement used for the model was of very high strength. However, after plotting the experimental results of the last two shaking table tests, and considering the observed behavior of the last shaking table it was concluded that the mode of failure probably occurred for both reasons, the short reinforcement length plus the big strength that the textile carried.

VII- DISCUSSION

In the coming tests the surface of failure that was reflected by the bending of the solders will be improved by the use of soil displacement markers, and a different geosynthetic will be used. Although the geosynthetic reinforcement will still be a non-woven heat bonded geotextile, its strength will be less than the strength of the most recent geotextile. The new telltales will be used for the tests left under Adam Pérez direction and are expected to show a more efficient and clear representation of the mode of failure performed in the shaking table test. Additionally, a more detailed view of the horizontal and vertical displacements throughout the slope will be obtained.