# FAILURE MECHANISMS AND DEFORMATION MODES OF REINFORCED SOIL WALLS

**Sabermahani, M. [1], Ghalandarzadeh, A. [2], Fakher, A. [3]**
[1] *Ph.D. Student of Geotechnical Engineering, Civil Engineering Faculty, Tehran University*
[2] *Assistant Professor, Civil Engineering Faculty, Tehran University*
[3] *Associate Professor, Civil Engineering Faculty, Tehran University*

**Abstract**: A series of 1/5 scaled reinforced soil wall shaking table tests, with 1m height, were conducted using two categories of reinforcements named weak and strong types based on 2% strain tensile stiffness. Physical models were subjected to constant acceleration amplitude sinusoidal input motion with various frequencies: 2, 5, 8 and 10 Hz. Different parameters of the model such as reinforcement length, spacing, stiffness, and soil density were changed and variation of seismic response of the wall was studied. Two different failure mechanisms and deformation modes i.e. overturning and bulging were observed and tensile stiffness was found as the most effective parameter on formation of these modes. Based on all the observations it is concluded that ultimate tensile strength that is used as the main parameter for wall design in existing codes, is not a key parameter to influence wall seismic response, failure mechanism and deformation mode. Instead, reinforcement stiffness (at low strains, about 2%) is more important and determinant, but magnitude of response changes are not in equal order with stiffness changing.

**Keywords:** seismic behaviour, failure mechanism, deformation, physical modelling, reinforced soil wall, reinforcement stiffness

## INTRODUCTION

Application of reinforced soil walls has been increasing worldwide due to their cost effectiveness and satisfactory seismic performance. Available database revealed excellent performance of reinforced soil walls during large earthquakes and there are inconsequential collapse or failure reports. Nova-Roessig (1999) summarized a review of field performance, shaking table and centrifuge tests on reinforced soil structures.

Displacement-based analyses will become more important as engineers focus on performance-based (serviceability-based) design. This is an area of future research investigation (Koseki *et al*. 2006).

Current method for seismic design of reinforced soil walls (Bathurst (NCMA) 1998 and FHWA 2001) is based on limit equilibrium method using Mononobe-Okabe earth pressure theory, considering two main conditions:

- Their minimum strength selected to sustain proportional lateral earth pressure distributed vertical spacing between layers (Sv)
- Their minimum length selected in a way to satisfy adequate anchorage length and enough for base sliding resistance

However, some codes such as FHWA 2001 recommend that for peak ground acceleration more than 0.3g, Newmark sliding block analysis for estimation of wall displacement should be done. Developments of Newmark method for reinforced soil walls are available in literature. (Kramer and Paulsen 2004 ; Bathurst and Alfaro 1996; Bathurst et al. 2002; Cai and Bathurst 1996). These analysis methods do not fully account for the influence of reinforcement stiffness on wall response (El-Emam and Bathurst 2007).

Wall deformations provided by all aforementioned methods will be uniform across the wall face. This assumption contradicts the observed wall behavior reported by others. For example, Siddharthan *et al.* (2004) observed from centrifuge tests that the wall face displacement was not uniform across the wall face, and typically the middle of the wall displayed the largest displacement. Matsuo *et al.* (1998) reported for walls with discrete facings, the reinforced soil moved outward and the maximum displacement occurred at the mid-height of the wall. Ling *et al.* (2005) observed maximum deformation at the top of large scale walls subjected to scaled Kobe earthquake. Koseki *et al.* (1998) reported that all major failure modes for two types of reinforced soil walls they used were overturning with tilting of the wall face. They reported that all of the walls failed due to overturning and tilting of the wall face, and simple shear and multiple failure planes formed during shaking. They pointed out that the residual deformation of reinforced soil-type walls accompanied simple shear deformation along horizontal planes in the reinforced backfill.

Sakaguchi *et al.* (1996) reported that the largest lateral displacement and geotextile strain occurred at the top of the walls. Howard *et al.* (1998) reported that the maximum displacement was observed to occur above the mid-height of the walls.

Watanabe *et al.* (2003) found at their shaking table tests with very dense sandy soil backfill that overturning mode is predominant in GRS wall. In a case study, Koseki and Hayano (2000) discussed about a segmental-type wall using concrete block and poor backfill with reinforcement spacing more than NCMA recommendations that failed because of reinforcement-block connection failure and showed bulging of facing at Chi-Chi earthquake (1999). In an analytical modeling, Ling *et al.* (2005) found that the point of maximum lateral displacement due to earthquake was at the upper portion of the wall and the largest point of settlement was behind the rear end of the reinforcement.

Generally, 1g reduced scale physical model testing using shaking table is the most common approach to gain qualitative and quantitative insights into the seismic behavior of reinforced soil wall systems. A disadvantage of reduced scale tests is that the response of the model may be influenced by low confining pressure, far end boundary conditions of the shaking table box, and improperly scaled mechanical properties of the reinforcement. Nevertheless, qualitative insights are possible using this experimental approach. Furthermore, the models can be used to develop and validate numerical codes that can be used in turn to investigate wall response at prototype scale. In this research, seismic deformation modes of reinforced soil walls will be studied using 1g shaking table tests.

## SHAKING TABLE TESTS

A total number of 20 shaking table tests was carried out on reinforced soil walls. The tests were done using a shaking table with theses specifications:

- deck dimension: 1.8 * 1.2 $m^2$
- hydraulic jack capacity : 60 kN
- hydraulic jack displacement course : 250 mm
- electronic card A/D, D/A speed : 100 kHz
- model box dimension: 0.80 * 1.23 * 1.82 $m^3$

A container box was fabricated from rigid, transparent Plexiglas sheets to make wall deformations and behaviour visible. Various model parameters such as length, spacing and stiffness of reinforcements, soil density, amplitude, frequency and duration of input motion were changed in different tests to find the effect of these parameters on the seismic response of the wall, with emphasis on the amount and modes of deformation. A brief description of the various parameters adopted in the tests is given in Table 1.

**Table 1.** Brief description of tests

| TEST No. | $a_{max}$ (g) | Frequency (Hz) | L/H | Sv/H | Wall Type | Geosynthetic Type | J (N/m) | $T_u$ (N/m) |
|---|---|---|---|---|---|---|---|---|
| TEST 01 | 0.2 | 5 | 0.7 | 0.1 | Strong | yw-m | 9400 | 1700 |
| TEST 02 | 0.3 | 5 | 0.7 | 0.1 | Strong | yw-m | 9400 | 1700 |
| TEST 03 | 0.3 | 8 | 0.7 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 04 | 0.3 | 8 | 0.9 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 05 | 0.3 | 8 | 0.5 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 06 | 0.3 | 5 | 0.5 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 07 | 0.15 | 10 | 0.7 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 08 | 0.2 | 2 | 0.7 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 09 | 0.1 | 10 | 0.5 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 10 | 0.2 | 10 | 0.7 | 0.1 | Strong | li-t | 29000 | 600 |
| TEST 11 | 0.1 | 2 | 0.7 | 0.2 | Strong | yw-m | 9600 | 1300 |
| TEST 12 | 0.3 | 5 | 0.7 | 0.1 | Strong | yw-m | 9600 | 1300 |
| TEST 13 | 0.1 | 10 | 0.9 | 0.1 | Failed | pk-t | 90 | - |
| TEST 14 | 0.15 | 10 | 0.7 | 0.1 | Weak | bu-t | 115 | 200 |
| TEST 15 | 0.1 | 10 | 0.7 | 0.1 | Weak | wh-t | 260 | 3920 |
| TEST 16 | 0.1 | 10 | 0.7 | 0.1 | Weak | bk-t | 190 | 1000 |
| TEST 17 | 0.15 | 5 | 0.7 | 0.1 | Weak | bk-t | 190 | 1000 |
| TEST 18 | 0.15 | 5 | 0.7 | 0.1 | Weak | wh-t | 260 | 3920 |
| TEST 19 | 0.1 | 2 | 0.7 | 0.1 | Weak | wh-t | 260 | 3920 |
| TEST 20 | 0.15 | 5 | 0.5 | 0.1 | Weak | wh-t | 260 | 3920 |

One main objective of this research was to study the effect of reinforcement stiffness on GRS wall response. Two different categories of reinforcements consist of very low stiffness (very extensible) and relatively high stiffness (extensible) materials were selected. The tests can therefore be divided into two series: "strong type" reinforced soil wall tests and "weak type" reinforced soil wall tests.

## MODEL GEOMETERY

To be consistent with previous shaking table studies conducted by other researchers, all physical models were constructed with 1.0 m height. With consideration to the height of traditional walls between 3.0 m and 7.0 m with an average of 5.0 m, a 1.0 m height model with a scale factor equal to 5.0 is a good physical model to simulate seismic behaviour of geosynthetic reinforced soil walls. Figure 1 illustrates a schematic geometry of the model used for the present research.

A firm 15 cm thick layer was used as the foundation soil for all models. All walls except Wall 11 was constructed in 10 layers of 10 cm thickness. Wall 11 only was built in 5 layers of 20 cm thickness.

Wrap-around type wall facing was selected. This type of facing was used to prevent any complication of reinforced soil wall interaction with any structural rigid facing. By using wrap-around facing, all potential modes of wall deformation and failure mechanisms can be visible, whereas using rigid full-height planar facings allowed overturning and tilting translational modes only.

Bathurst *et al.* (2002) presented wall displacements for models with different facing types and showed that vertical walls with full height rigid facing provide better resistance and have smaller deformation in comparison with segmental block facing wall with no shear connections. Walls with wrap-around facing expect to show more displacements than other facing types, because there is no structural stiff member to provide the walls with additional rigidity to withstand lateral displacements.

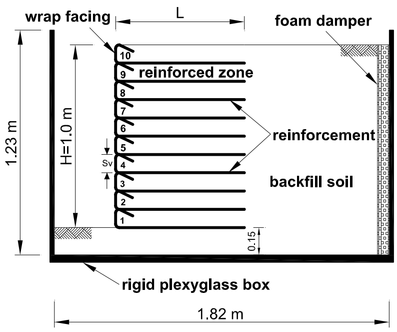



**Figure1.** schematic view of physical models

## MODEL CONSTRUCTION PROCEDURE

After construction of the foundation layer and laying of the first layer of reinforcement sheet on the foundation soil, soil filling using a mechanical gravitational soil raining system was carried out. For facing support during construction, a rigid frame was used as partial temporary support at the face of the wall. Using the facing frame was essential for achieving identical good compaction and relative density at the facing. After partial backfilling and folding of the reinforcement at the face, the remaining backfilling was carried out on the overlap length of the reinforcement, until the next layer was reached. A textile sheet was used at the face with 10 cm up and down tail and lateral flaps in each layer to retain the backfill material at the wall face.

After reaching the next layer elevation, face frame was removed and different colour sand layer was filled at the box wall boundary to separate each layer from others and to make deformations visible during shaking. During construction, each sensor was laid at its predefined place within the soil mass.

## INSTRUMENTATION

Acceleration and deformations were measured using accelerometers and displacement transducers (LVDT sensors) respectively. Acceleration sensors were laid at predefined positions during layer by layer construction of the wall. One acceleration sensor was attached at the box base to measure base acceleration. Measurement of facing deformation was done using LVDTs attached to a rigid column connected to the box body with a stiff beam. Deformation of the facing was measured at 5 levels from bottom to top.

Settlements of the wall top in the reinforced zone and in the backfill (in some tests) were measured with vertical LVDTs connected to the box frame with stiff beams. Various types of instrumentations were used for this series of tests but the position of displacement sensors was identical in all tests. Figure 2 shows one of the types used for monitoring of the models.

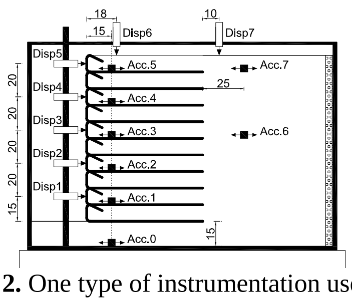



**Figure 2.** One type of instrumentation used in monitoring deformations

## CONSTRUCTION MATERIAL

Two main construction materials used for the physical models were soil and reinforcements.

### Soil

Firuzkooh 161 Sand was used for the construction of the reinforced soil wall and as backfill soil. The gradation curve for Firuzkooh sand is similar to that for Toyora sand. Figure 3 and Table 2 illustrate some properties of this standard soil type. The bulk unit weight was controlled to be constant at about 1.5 ton/m$^3$ in a loose state and at about 1.63 ton/m$^3$ in a dense state. The relative density of the soil in loose state was therefore about 47%, and in denser state was about 84%. Repeated experiences of soil pluviation helped to regulate the deposition in these tests and it was possible to achieve the target relative density. Considering scale factors between prototype and model, soil used in models should behave less stiff than field structure, target relative density was therefore chosen lower than field density. This approach was consistent with other researches.

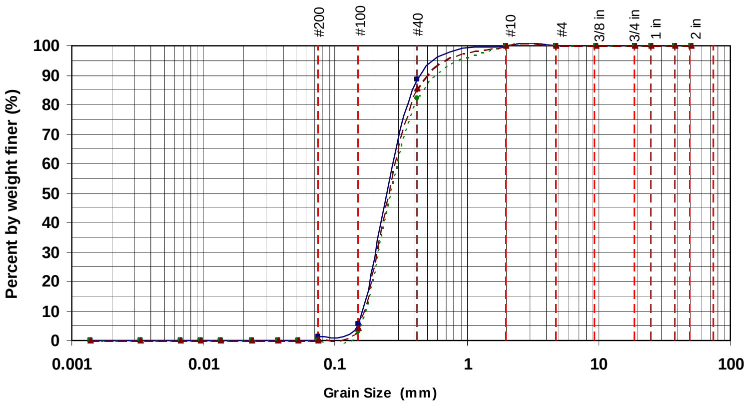



**Figure 3.** Gradation curve of Firuzkooh Sand

**Table 2.** Firuzkooh Sand properties

| USCS Name | $D_{10}$ (mm) | $D_{30}$ (mm) | $D_{50}$ (mm) | $D_{60}$ (mm) | Passing #200 % | Sand % | Cu | Cc | $\phi$ degree | $e_{max}$ | $e_{min}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SP | 0.16 | 0.21 | 0.27 | 0.3 | 1 | 99 | 1.87 | 0.88 | $40^0$ | 0.874 | 0.548 |

### Reinforcements

For soil reinforcement, 6 types of traditional sartorial textiles and plastic meshes were used. They can be categorized into two series (weak and strong) according to their tensile stiffness at 2% strain. These two types of material were selected to determine if there is any detectable difference in wall response due to a large difference in reinforcement stiffness.

Tensile strength and unit width stiffness were measured according to ASTM-D 4595 “Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method”.

Descriptions of the strong and weak geosynthetics used in the tests, tensile stiffness and ultimate tensile strength measurements are provided in Table 1. As can be seen from Table 1, weak and strong type categorization was based on tensile stiffness. Considering ultimate tensile strength, some weak type reinforcements (with low stiffness at 2%) have higher ultimate tensile strength than some of the strong type reinforcements (comparing wh-t type and bu-m type) and vice versa (comparing li-t type and bk-t type).

## INPUT MOTIONS

For parametric study and simple interpretation of results and quantitative comparisons, sinusoidal constant amplitude records were selected as base excitation. Physical models were subjected to 2, 5, 8, and 10 Hz frequency input motion in different tests. Each model was subjected to sequential different excitations from weak (low amplitude) to strong (high amplitude) peak base acceleration. Totally more than 77 harmonic time histories were applied to 20 models. However, because of soil densification and deformation tolerated by the models after first motion, just results of first model excitation were used and interpreted in this paper.

## MODES OF DEFORMATION AND FAILURE MECHANISM

A general review of literature revealed that, reinforced soil walls subjected to seismic loading in real earthquake events, or centrifuge or shaking table tests have shown two main deformation modes, i.e. overturning or bulging. Bulging of the wall is indicated by smaller wall deformations at the top and bottom of the wall relative to mid-height, while overturning is indicated by maximum wall deformation at the top. In many cases, base sliding is also observed with these two modes.

The focus of this research was to observe different modes of wall deformation and to identify important effective parameters that have main influence on the formation of deformation mode and their impact.

Therefore, with a predefined plan, tests were started with strong type reinforcements. During the first 12 tests using strong type reinforcements, deformation mode of the wall was base sliding plus overturning. With this mode of deformation, maximum displacement occurred at the top of the wall and the reinforced zone deformed in simple shear manner and moved similar to a rigid block. Multi-line failure surface formed behind the reinforced zone within the backfill. Figure 4 shows the deformation mode of a reinforced soil wall with failure surfaces within the backfill. Outward movement of the reinforced zone resulted in large lateral deformations within the backfill soil and multi-line parallel failure surfaces consistent with active earth pressure theory. Failure surfaces in almost all 12 strong type wall tests extended to second or third layer of reinforcement. This observation was consistent with Richardson and Lee (1975) who reported formation of linear failure surfaces, generally initiated in the backfill and extended through the second or third layer of (aluminum foil sheet) reinforcements.

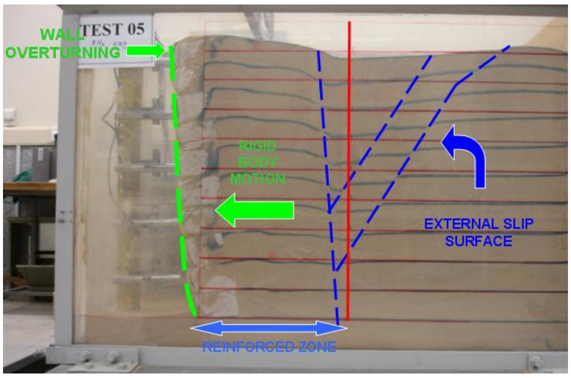


**Figure 4.** Deformation mode and failure surface of strong type walls

With this mode of deformation, maximum settlement occurred behind the reinforced zone, and surface settlement profile was as a stepped-shape brittle line. Howard *et al.* (1998) observed that maximum settlements occurred just behind the reinforced zones due to the movement of the wall away from the backfill.

As is visible in Figure 4, the end of the reinforcement layers moved downward due to drag-down forces generated behind the reinforced zone. The real predominant mode of deformation for the strong type wall tests was simple shear mode that was in fact different from overturning or base sliding of rigid body as assumed by some limit equilibrium based methods, but for simplicity is named overturning.

After 12 tests with varying length or spacing of reinforcements, soil density, or frequency and acceleration amplitude of base excitation, it was observed that there was no change of deformation mode, i.e. overturning mode of deformation (with maximum displacement at top of the wall). Subsequent tests were carried out with reinforcement stiffness changed. Weak type material consists of very extensible textiles was selected.

With weak type material, static and pseudo-static design safety factors considering ultimate tensile strength was satisfied. All walls built with weak type reinforcements using construction procedure exactly the same as walls built with strong type reinforcement, with the exception of Wall 13, was stable statically. For the construction of Wall 13, the weakest type of reinforcement (pk-t) was used. Consequently, Wall 13 suffered from bulging deformation at the end of construction. As deformation progressed, a unique failure surface was formed within the reinforced zone. Figure 5 shows the end of construction deformation and slip surface of Wall 13.


**Figure 5.** Deformation mode and failure surface of wall No. 13 - (end of construction)

After the failure of Wall 13, more extensible material with lower stiffness than strong type textiles was used in Tests 14 to 20. All walls of Test 14 to 20 were stable at the end of construction and no considerable deformation was measured before shaking. With weak type walls, several parameters such as length of reinforcement and frequency and acceleration amplitude of input motion were changed, but the final deformation mode remained the same. Failure surface of weak walls formed within the reinforced zone and the mode of deformation was bulging (with maximum displacement somewhere between the top and bottom of the wall). Figure 6 shows the bulging deformation mode of reinforced soil wall and failure surface within the reinforced zone.

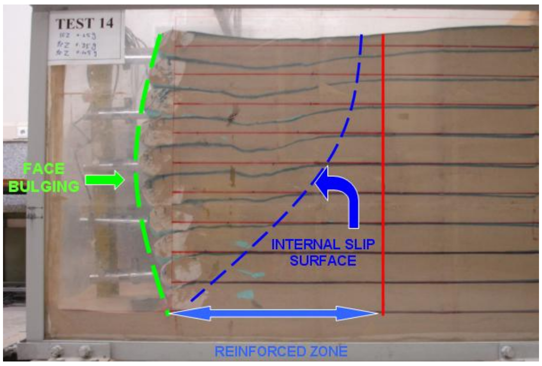
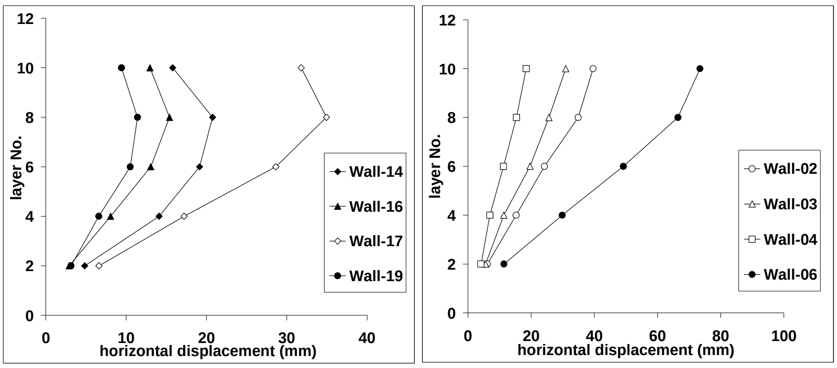



**Figure 6.** Deformation mode and failure surface of weak type walls

Maximum settlement with this mode of deformation was at the middle of the reinforced zone, and the surface settlement profile was a continuous curved spoon shape line.

Facing deformation profiles of four strong type walls and four weak type walls are shown in Figure 7. As can be seen from this figure, deformation mode with all strong type walls (1 to 12) was overturning and with weak type walls (14 to 20) was bulging. The different deformation values for the different walls were because of varying parameters such as wall geometry, material stiffness and input motion.




**(a)** **(b)**

**Figure 7.** Modes of deformation :
(a) bulging mode at weak type walls; (b) overturning mode at strong type walls

**Acknowledgment:** The writers would like to acknowledge MESIRAN Co. and Mokarrar Geosynthetic Co. for their support of this research and wish to extend special thanks to Mr. Joleiny and Mr. Elahi for their help in the physical model construction and testing.

## REFERENCES

ASTM, Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method, Designation: D 4595 – 86 (Reapproved 1994), ASTM Standards, Vol 07.01.

Bathurst, R.J., 1998.NCMA segmental retaining wall seismic design procedure- supplemented to design manual for segmental retaining walls (second edition 1997) published by National Concrete Masonry Association , Herndon, VA, 187 p.

Bathurst, R.J., Hatami, K. and Alfaro, M.C., 2002. Geosynthetic reinforced soil walls and slopes: seismic aspects. Geosynthetics and their applications (S.K. Shukla Ed.), Thomas Telford, 327-392.

Bathurst, R.J., Alfaro, M.C., 1996. Review of seismic design, analysis and performance of geosynthetic reinforced walls, slopes and embankments, Keynote paper. In: Ochiai, H., Yasufuku, N., Omine, K. (Eds.), Proceeding of the International Symposium on Earth Reinforcement. Fukuoka, Kyushu, Japan, 12–14 November 1996. vol. 2. Balkema, Rotterdam, pp. 887–918.

Cai, Z., Bathurst, R.J., 1996. Seismic induced permanent displacement of geosynthetic reinforced segmental retaining walls. Canadian Geotechnical Journal 31, 937-955.

El-Emam, M. M., Bathurst, R. J., 2007. Influence of reinforcement parameters on the seismic response of reduced-scale reinforced soil retaining walls. Geotextiles and Geomembranes, 25(1), 33-49.

FHWA, 2001. Mechanically stabilized earth walls and reinforced soil slopes: Design and construction guidelines, publication FHWA NHI-00-43, Federal Highway Administration and national Highway Institute, Washington, DC, USA.

Howard, R.W.A, Jr., Kutter, B.L. and Siddharthan, R., 1998. Seismic deformation of reinforced soil centrifuge models, Proceedings of the 3rd Geotechnical Earthquake Engineering and Soil Dynamics Conference, Spec. Pub. No. 75, Volume 1, pp. 446-457.

Koseki, J., Bathurst,R.J., Guler, E., Kuwano, J., Maugeri, M., 2006. Seismic stability of reinforced soil walls. Keynote paper, 8th international conference on geosynthetics (8ICG), Yokohama, Japan, Vol. 1, pp. 51-77.

Koseki, J. and Hayano, K., 2000. preliminary report on damage to retaining walls caused by the 1999 Chi-Chi earthquake. Bulletin of ERS, in statute of industrial science, University of Tokyo, 33, 23-34.

Koseki, J., Munaf, Y., Tatsuoka, F., Tateyama, M.,Kojima , K., and Sato, t., 1998. Shaking and tilt table tests of geosynthetic-reinforced soil and conventional-type retaining walls, geosynthetics international , vol. 5, nos. (1-2), pp 73 – 96.

Kramer, S. L. and Paulsen, S. B., 2004. Seismic performance evaluation of reinforced slopes. Geosynthetics International, vol. 11, No. (6), 429–438.

Ling H. I., Liu , H., and Mohri ,Y., 2005. Parametric Studies on the Behavior of Reinforced Soil Retaining Walls under Earthquake Loading , Journal of Geotechnical and Geoenvironmental engineering, ASCE, 131(10), 1056-1065.

Ling , H.I., Mohri, Y., Leshchinsky, D., Burke, C., Matsushima, K. and Liu, H., 2005. Large scale shaking table tests on modular-block reinforced soil retaining walls, Journal of Geotechnical and Geoenvironmental engineering, ASCE, 131(4), 465-476.

Matsuo, O., Tsutsumi, T., Yokoyama, K., Saito, Y., 1998. Shaking table tests and analysis of geosynthetic-reinforced soil retaining walls. Geosynthetics International, vol. 5, nos. (1–2), 97–126.

Nova-Roessig, L. 1999. “Centrifuge studies of the seismic performance of reinforced soil structures,” Ph.D Dissertation, University of California, Berkeley, 233 pp.

Nova-Roessig, L. and Sitar, N., 1999. Centrifuge model studies of the seismic response of reinforced soil slopes. Proceeding of the 2nd International Conference on Earthquake Geotechnical Engineering, (Eds. Seco and Pinto), 679-684.

Richardson, G. N., and Lee, K. L. 1975. Seismic design of reinforced earth walls., J. Geotech. Eng. Div., Am. Soc. Civ. Eng., 101(2), 167– 188.

Sakaguchi, M., 1996. A study of the seismic behaviour of geosynthetic reinforced walls in Japan. Geosynthetics International, 3 (1),13–30.

Siddharthan.R.V., Ganeshwara V., Kutter B. L., El-Desouky M. and Whitman R. V., 2004. Seismic Deformation of Bar Mat Mechanically Stabilized Earth Walls. I: Centrifuge Tests. ASCE, 130(1), 14-25.

Watanabe, K., Munaf, Y., Koseki,J. Tateyama, M. and Kojima,K., 2003. Behavior of several types of model retaining walls subjected to irregular excitation, soils and foundations, 43(5), 13-27.