Time-domain analysis of frictional base isolation using geosynthetics

Arab, M.G. & Kavazanjian Jr, E.
Department of Civil, Environmental and Sustainable Engineering, Arizona State University, Tempe, Arizona, USA

Keywords: base isolation, geosynthetics, interface shear strength, seismic, earthquake, time domain

ABSTRACT: The low interface shear strength of many geosynthetic interfaces offers the potential for cost effective seismic hazard mitigation by frictional base isolation. To facilitate engineering evaluation of performance, previous investigators have suggested values of equivalent linear stiffness and damping for use in frequency-domain seismic response analyses of geosynthetic base isolation systems. However, time-domain finite difference analyses using an elastic-perfectly plastic interface model indicate that frequency-domain analyses conducted using these equivalent linear parameters may significantly underestimate the seismic response of a frictional base isolated mass subject to earthquake-generated strong ground motions. Underestimation of the response is attributed to the use of damping values from uniform sinusoidal loading tests for the duration of the earthquake time history. Additional analyses are required to develop practical recommendations for use of frequency domain analysis in design of geosynthetic base isolation systems.

1 INTRODUCTION

The low in-plane shear strength of many geosynthetic interfaces has inspired research into the use of geosynthetic materials as an economical means of frictional seismic base-isolation of foundations. In principle, the shear stress transmitted to an overlying foundation or structural slab subject to earthquake strong ground motions is limited to the minimum in-plane shear strength of the underlying layers. Application of this principle to reduce the intensity of the design motions for the overlying structure is referred to as frictional base isolation (Skinner et al., 1993). Key parameters describing the performance of a frictional base isolated structure include the maximum relative displacement between the structure and the ground and the residual permanent displacement and spectral accelerations (including the peak ground acceleration) of the structure.

Kavazanjian et al. (1991) and Yegian and Lahlaf (1992) independently suggested that the low shear strength of geosynthetic interfaces could be used to provide economical frictional base isolation for engineered structures. Both of these teams conducted shaking table tests on a rigid block underlain by a layered geosynthetic system to demonstrate the feasibility of geosynthetic base isolation. Yegian and Kadakal (1998) and Yegian and Kadakal (2004) conducted additional testing and analyses to evaluate the concept of using geosynthetic materials for frictional base-isolation beneath building foundations.

Yegian et al. (1998) provided recommendations for equivalent linear damping and stiffness to account for the presence of a low shear strength geosynthetic interface in an equivalent linear frequency domain seismic response analysis based upon the results of uniform sinusoidal loading shaking table tests. To evaluate the adequacy of the equivalent linear procedure proposed by Yegian et al. (1998), non-linear time-domain numerical analyses of the response of geosynthetic base isolation systems were conducted using the computer program FLAC (Itasca 2008). A simple linear elastic-perfectly plastic Mohr-Coulomb constitutive model was used to model the cyclic shear behavior of the interface. The numerical model was calibrated using the results of uniform sinusoidal and non-uniform earthquake-type loading shaking table tests of a rigid block on top of a layered geosynthetic system. Nonlinear time-domain analyses of a geosynthetic base isolated rigid block subject to earthquake time histories conducted using the calibrated model were compared to the results of equivalent linear analyses conducted using the recommendations of Yegian et al. (1998). This comparison suggests that analyses conducted according to the Yegian et al. (1998) recommendations may significantly under predict the response of a geosynthetic base isolation system.

2 NUMERICAL MODEL CALIBRATION

Kavazanjian et al. (1991) conducted a series of shaking table tests on a rigid block with one geosynthetic material glued to the bottom of the block and a second geosynthetic material secured to the top of the shaking table. Four combinations of geotextile and geomembrane materials were subject to uniform sinusoidal motions of varying amplitude. Three of the combinations were also subjected to a non-uniform motion based upon the S90W component of the 1940 El Centro earthquake. The acceleration of the block and the displacement of the block relative to the shaking table were monitored during the tests.

To model the Kavazanjian et al. (1991) shaking table tests in the non-linear time domain analyses, the two-layer, nine element mesh shown in Fig: 1 was used. The upper layer represents the rigid block and the lower layer represents the shaking table. The block and shaking table were assigned the bulk and shear modulus of structural steel. An interface element was used between the upper and lower layers of the mesh. The interface element was assigned an elastic stiffness approximately equal to ten times the bulk modulus of the mesh elements. The input motion was applied as a shear stress time history to the base of the mesh to model the input motion.

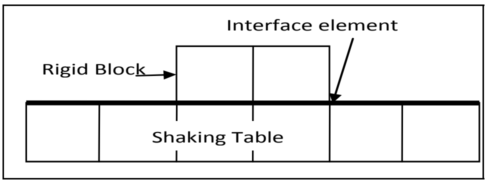

Figure 1. Finite difference mesh for non-linear model.

Fig: 2 shows a comparison between the block acceleration measured in one of the uniform sinusoidal loading tests and the results calculated in the non-linear finite difference time domain analysis.

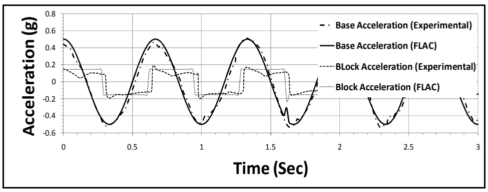

Figure 2. Measured and calculated accelerations during uniform sinusoidal loading

The test in Fig: 2 was conducted using a geomembrane/geotextile interface with a measured static coefficient of friction equal to 0.16. However, the numerical analyses results shown in Fig: 2 were calculated using a friction coefficient of 0.15 in the Mohr-Coulomb interface model. These results suggest that the dynamic coefficient of friction for the interface may be slightly different than the static interface friction coefficient. A similar conclusion was reached by Kavazanjian et al. (1991) based on interpretation of the experimental results.

Fig: 3 presents a comparison of the relative displacement of the rigid block as measured on the shaking table test and as calculated in the numerical analysis. The small discrepancies between the experimental results and the numerical analysis may be attributed to the somewhat non-uniform behavior in the experimental results: note the somewhat non-uniform acceleration behavior of the block in Fig: 2 and the slight drift towards increasing peak displacement in the negative direction in Fig: 3. Despite the small differences between experimental and numerical results like those shown in Fig: 2 and Fig: 3, additional numerical analyses of the Kavazanjian et al. (1991) test results suggest that the numerical model is capable of reproducing the results of uniform sinusoidal loading shaking table tests if the appropriate interface shear strength is employed.

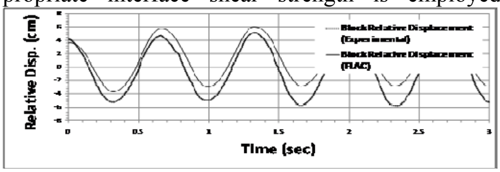

Figure 3. Measured and calculated relative displacement during uniform sinusoidal loading.

Yegian and Kadakal (2004) report on shaking table tests of a geosynthetically base isolated rigid block using both uniform sinusoidal acceleration input and an earthquake-like acceleration input. Based upon initial tests on different layered geosynthetic configurations, Yegian and Kadakal (2004) chose a nonwoven geotextile-medium density polyethylene layered system (denoted Geotextile/UHMWPE) for their base isolation work. The Geotextile/UHMWPE interface was chosen because this interface showed a constant coefficient of friction independent of frequency of loading, normal stress, and velocity of sliding. Yegian and Kadakal (2004) conducted a suite of uniform sinusoidal loading tests at frequencies of 1, 2, 3, and 5 Hz with acceleration amplitudes varying from less than 0.1 g to 0.7 g.

The numerical model shown in Fig: 1 was also used to reproduce the uniform sinusoidal loading tests conducted by Yegian and Kadakal (2004). Fig: 4

presents a comparison of the maximum relative displacement between the block and the shaking table as reported by Yegian and Kadakal (2004) and as calculated in the numerical analysis. In Fig: 4, the open symbols represent the experimental results and the closed symbols represent the numerical results.

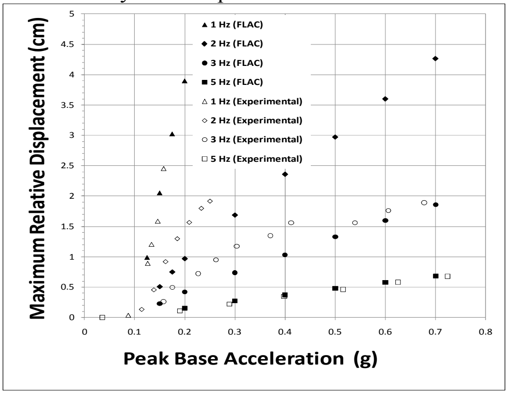

Figure 4. Maximum relative displacement from experimental results and equivalent linear and non-linear analysis.

Fig: 4 shows generally good agreement between the experimental results and the numerical analysis although there are some discrepancies between predicted and observed results in the range of 0.1 to 0.4 g for the test at 2 Hz and 3 Hz.

Yegian et al. (1998) and Yegian and Kadakal (2004) conducted shaking table tests of a rigid block with a smooth HDPE/nonwoven geotextile interface and the Geotextile/UHMWPE interface, respectively, using earthquake motions as input. Yegian et al. (1998) used the Los Angeles University Hospital Grounds record from the 1994 M.6.7 Northridge earthquake scaled to 0.9g. Yegian and Kadakal (2004) used the Corralitos, Capitola, and Santa Cruz records from 1989 M 7.1 Loma Prieta earthquake scaled to peak accelerations of 0.1 g to 0.4 g.

The time domain numerical model was also used to simulate the Yegian et al. (1998) and Yegian and Kadakal (2004) tests that used the earthquake time histories as input. Because the earthquake motion is asymmetric, both the shaking table tests and the numerical analyses yield a residual permanent displacement. Fig: 5 shows a comparison between the residual permanent displacement from the shaking table tests as reported by Yegian et al. (1998) and Yegian and Kadakal (2004) and the permanent displacement calculated using the numerical model.

Comparison of residual permanent displacement from the experimental results and the non-linear analysis in Fig: 5 shows generally good agreement. The primary discrepancy is for the Corralitos record from the Loma Prieta event. The calculated permanent displacement for the Corralitos record is less than the displacement measured experimentally in the 0.1 g to 0.25 g range, although both calculated and experimental results show a similar trend of increasing displacement with increasing of the base peak acceleration. One interesting aspect of the results is that in some cases the permanent displacement decreases as base acceleration increases.

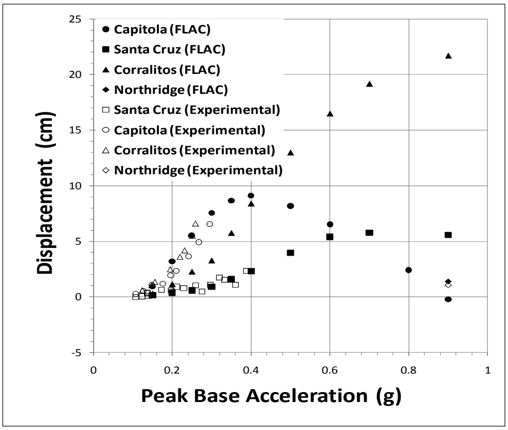

Figure 5. Residual permanent displacement from experimental results and equivalent linear and non-linear analysis.

3 COMPARISON OF FREQUENCY AND TIME DOMAIN ANALYSES

A series of seismic response analyses of a geosynthetically isolated rigid block with a friction coefficient of 0.1 were conducted using the Santa Cruz record from the Loma Prieta earthquake scaled to peak accelerations from 0.1 g to 0.7 g. Both equivalent linear analyses using the interface model of Yegian et al. (1998) and non-linear time-domain analyses using the numerical model shown in Fig: 1 were conducted. Fig: 6 compares the acceleration response spectra of the rigid block calculated in a frequency domain analysis to the results from the non-linear time domain analysis.

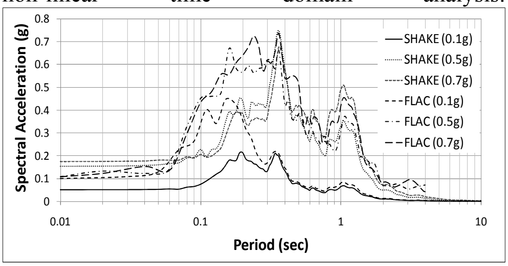

Figure 6. Acceleration response spectra from equivalent linear and non-linear analysis.

Fig: 6 shows that the equivalent linear analysis significantly under predicts the spectral acceleration of the block at spectral periods of less than 0.5 s. At longer periods, spectral accelerations calculated in the equivalent linear analysis are similar to values from the non-linear time domain analysis. This discrepancy at short periods may be attributed to the use of the relative high value of 0.45 for the equivalent linear damping ratios suggested by Yegian et al. (1998), as this will dampen the high frequency motions that contribute to structure motions below the yield acceleration of the base isolation system.

Fig: 7 compares the time history of displacement for the Capitola record from the Loma Prieta earthquake scaled to 0.25 g from an equivalent linear analysis using the interface model of Yegian et al. (1998) to numerical analyses conducted using the non-linear time domain model and to the results of a shaking table test by Yegian and Kadakal (2004) that used the same time history. The equivalent linear analysis did not predict any permanent displacement. Furthermore, the maximum transient displacement predicted in the equivalent linear analysis was significantly less than the values from the numerical analysis and the displacement measured in the shaking table test. However, the predicted permanent displacement in the numerical analysis showed good agreement with experimental results.

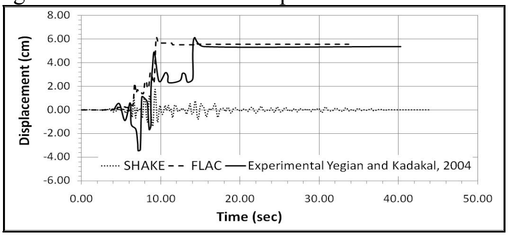

Figure 7. Relative displacement from Yegian and Kadakal (2004) and equivalent linear and non-linear analysis.

4 SUMMARY AND CONCLUSIONS

The ability of a low shear strength geosynthetic interface to provide frictional base isolation has been demonstrated through laboratory shaking table and centrifuge experiments (Kavazanjian et al. (1991); Yegian and Lahlaf (1992); Yegian et al. 1998, and Yegian and Kadakal (2004). A non-linear time domain model of a geosynthetically isolated block on a horizontal plane was developed to model these tests using a Mohr-Coulomb elastic-perfectly plastic interface model. This model was shown to reproduce shaking table tests that employed sinusoidal and earthquake-like input motions with good accuracy.

Analyses of a geosynthetically isolated block on a plane subject to an earthquake time history were conducted using both the non-linear time domain model and a frequency domain analysis that employed the procedure proposed by Yegian et al. (1998). The results of these analyses show that the frequency domain model under predicts the maximum transient displacement of the block relative to the plane, the residual permanent displacement of the block, and the spectral accelerations of the block at periods less than 0.5 s. Therefore, while frequency domain analyses are an efficient and convenient way to model seismic response, the Yegian et al. (1998) recommendations for frequency domain modeling underpredict key elements of the response of a geosynthetic base isolation system. Additional analyses are required to develop recommendations for use of frequency domain analysis in the design of geosynthetic base isolation systems.

ACKNOWLEDGMENT

The work in this paper is part of a joint Arizona State University / Ohio State University research program titled *GOALI: Collaborative Research: The Integrity of Geosynthetic Elements of Waste Containment Barrier Systems Subject to Large Settlements or Seismic Loading.* This project is funded by the Geomechanics and Geotechnical Systems, GeoEnvironmental Engineering, and GeoHazards Mitigation program of the National Science Foundation Division of Civil, Mechanical, and Manufacturing Innovation under grant number CMMI-0800873. The authors are grateful for this support. The authors also wish to thank Dr. Neven Matasovic of Geosyntec Consultants for his help with the FLAC analyses described in this paper.

REFERENCES

Itasca Consulting Group, Inc. 2008. FLAC – Fast Lagrangian analysis of continua, user's manual.

Kavazanjian, E., Jr., Hushmand, B., and Martin, G.R. 1991. Frictional Base Isolation Using a Layered Soil-Synthetic Liner System." Proc., 3rd U.S. Conference on Lifeline Earthquake Engineering, ASCE Technical Council on Lifeline Earthquake Engineering Monograph No. 4, 1139-1151.

Skinner, R. I., Robinson, W. H., and McVerry, G. H., 1993. An introduction to seismic isolation. Wiley, New York.

Yegian, M.K., Harb, J.N., and Kadakal, U. 1998. Dynamic Response Analysis Procedure for Landfills with Geosynthetic Liners. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 124, No. 10, 1027-1033.

Yegian, M.K., and Kadakal, U. 1998. Geosynthetic Interface Behavior under Dynamic Loading. Geosynthetics International, Vol. 5, Nos. 1-2, 1- 16.

Yegian, M.K., and Lahlaf, A.M. 1992. Dynamic interface shear properties of geomembranes and geotextiles. Journal of the Geotechnical Engineering, ASCE, Vol. 118, No.5 pp. 760-779.

Yegian, M.K. and Kadakal, U. 2004. Foundation Isolation for Seismic Protection Using a Smooth Synthetic Liner. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 130, No. 11, 1121-1130.