8 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The development, calibration, and a validation of a numerical model capable of predicting seismically induced permanent displacements of reinforced steep slopes was presented in this thesis. Past experimental and analytical work, as well as established principles of geotechnical engineering, were used to develop and calibrate a single degree of freedom system model, called the reinforced modified Newmark model (RMNM). The RMNM was implemented in a FORTRAN program, SPSLOPE, which was used to estimate permanent displacements of an actual steep slope.

8.1 Summary

A review of the performance of reinforced soil structures when subjected to seismic loading, in the field and in laboratory model tests, was presented in order to provide insight into aspects of the behavior of these structures that should be considered in design. The tests conducted in the laboratory, including model centrifuge and shaking table tests, provide information on steep slope deformations at controlled levels of loading and duration, as well as provide insight into the mechanisms by which displacement occurs.

Current design approaches for reinforced soil structures stem from those of unreinforced slopes. Common methods of design of steep slopes and walls for static and dynamic conditions, were reviewed. Static stability analyses are typically based on limit equilibrium or stress deformation methods. Dynamic stability is predominantly based on pseudostatic analyses, which is an extension of limit equilibrium. Because pseudostatic methods provide no information regarding potential slope deformations, displacement based methods may be able to better represent the serviceability of a reinforced slope following a seismic event.

In order to develop a simple model capable of predicting seismically induced displacements, the behavior of reinforced structures tested in centrifuge shaking table tests, at the University of Washington and elsewhere were summarized and analyzed. The analytical modeling of reinforced structures, also conducted in conjunction with these tests, was presented.

The simplified model, called the reinforced modified Newmark model (RMNM), is based on the conventional rigid block Newmark analysis developed by Newmark in 1965 to predict seismically induced permanent displacements of a slope. The RMNM extends the modified Newmark model developed by Kramer and Smith (1995), which is capable of modeling the dynamic response of the soil above the failure surface using a compliant rigid block system. The modification of these models allows the RMNM to account for the influence of reinforcement on permanent displacements of MSE slopes.

The RMNM was calibrated using experimental and analytical data and in order to model the three primary mechanisms that influence permanent displacements of steep slopes: (1) shearing of the soil located within and behind the reinforced zone, (2) stretching of the reinforcing material, and/or (3) pullout of the reinforcement. A program called SPSLOPE was developed to map actual slope properties to the parameters of the RMNM. SPSLOPE estimates the permanent displacements of the actual slope for a particular acceleration time history.

A parametric study, using the properties of an actual reinforced steep slope, was conducted to determine the influence of the slope’s geometry, soil properties and the reinforcement, spacing, strength and stiffness on permanent displacements. The influence of the duration and frequency content of the acceleration input motion was also explored.

8.2 Conclusions

The fundamental behavior of reinforced slopes that was observed in past experimental and analytical research was used to develop the RMNM. Careful examination of the performance of reinforced steep slopes illustrate that:

1. *Deformation patterns are consistent with the development of a bilinear failure mechanism* – investigations have shown that large deformations frequently involve movement on a relatively flat failure surface that intersects the lower layers of the reinforced area and then extends more steeply towards the surface of the backfill. Because of this established pattern, a bilinear failure surface was assumed in the development of SPSLOPE and in the calibration of the RMNM.

2. *Movement of the failure mass is primarily translational* – Experimental tests have shown, through the use of embedded displacement markers, that the mechanism causing displacement of the slope is primarily translation, as opposed to walls that deform predominantly by tilting.

3. *Failure surfaces become flatter with increasing input motion amplitude* – Observations from shaking table tests and analytical modeling show that the failure surface flattens as the input motion increases, which is consistent with Mononobe-Okabe theory. The representation of the dynamic failure surface geometry in SPSLOPE was based on the peak horizontal acceleration causing downslope movement to account for this observed behavior.

4. *Displacements decrease with increasing reinforcement length* – The amount of displacement a reinforced slope experiences is logically dependent on the length of the reinforcement providing resistance to the slope. Slopes with longer reinforcement are typically more stable and have higher static factors of safety.

5. *Displacements increase with increasing reinforcement spacing* – Steep slopes designed with a larger spacing between the reinforcement reduce the number of layers to be constructed. Decreasing the number of layers also decreases the total resistance to deformation provided by the reinforcement.

6. *Displacements decrease with increasing reinforcement strength/stiffness* – Steep slopes reinforced with less stiff/ or weaker reinforcement tend to experience more displacement compared to slopes with more stiff/strong reinforcement.

These observed characteristics of the behavior of reinforced slopes supported the development of a sliding block model. Development and calibration of the RMNM indicated that:

1. A reasonable model for prediction of permanent displacements must account for permanent deformation due to soil shearing, reinforcement stretching, and pullout of the reinforcement.

2. The model must be calibrated in a manner that produces results that are consistent with expected performance, e.g. so that permanent displacements decrease with increasing reinforcement length, decreasing reinforcement spacing, and increasing reinforcement strength/stiffness.

3. The simplest system capable of modeling the mechanisms that produce permanent deformation is a sliding block model with a nonlinear spring in series with a Coulomb slider element.

4. The basic RMNM model produced reasonable results. Predicted displacements decreased as the inclination of the plane decreased, as the strength/stiffness of the spring increased and as the input acceleration decreased. Increased pullout resistance of the slider element also showed a decrease in predicted displacements.

5. SPSLOPE predicts permanent displacements that decrease as the reinforcement length increases, as the reinforcement strength/stiffness increases, and as the

reinforcement spacing decreases. This behavior is consistent with the previously established behavior observed in experimental tests and analytical modeling.

6. SPSLOPE is capable of providing reasonable estimates of permanent displacements for a wide variety of slopes with different reinforcement properties, length and spacings. SPSLOPE predicts experimentally observed displacements within a factor of 2. SPSLOPE is more likely to be conservative than unconservative, i.e. to overpredict, rather than underpredict, permanent displacements.

7. SPSLOPE is capable of producing good estimates of yield acceleration. The yield accelerations for the included tests were predicted within a range of 1.5.

A series of parametric analyses illustrated the sensitivity of permanent displacement to various reinforced slope characteristics. Interpretation of the results of these analyses with respect to displacement-based design indicates that:

1. Different slope characteristics have different degrees of influence on permanent displacements.

2. Increasing the length of the reinforcement approaches a point of diminishing returns with respect to permanent displacements. Once the reinforcement reaches a certain length, providing additional length provides very little benefit in terms of reducing permanent displacement. The contrast between this conclusion and the fact that pseudo-static design procedures predict significant improvements in stability with increased reinforcement length is important.

3. Reducing the spacing of the reinforcement also leads to diminishing benefits, although practical construction–related factors typically control the minimum spacing used in the field.

4. Permanent displacements are sensitive to the friction angle of the soil suggesting that accurate knowledge of soil strength characteristics is important for accurate estimation of permanent displacements.

5. Record-to-record variability between different ground motions can lead to large differences in estimated permanent displacements. Such estimates should be made using SPSLOPE with a suite of ground motions that reflects the range of amplitudes, frequency contents, and durations that could be expected at the site of interest.

8.3 Future Research

The calibrated RMNM, currently implemented in SPSLOPE, is capable of predicting permanent displacements of reinforced steep slopes. Extending the experimental database, in terms of reinforcement properties and in the shear quantity of good experimental data, used in the calibration process would increase the accuracy of the RMNM. This could be accomplished by adding the following:

1. Centrifuge tests with earthquake motions, including reports of time histories of displacement and yield accelerations.
2. Centrifuge tests with smaller *L*/*H* ratios.
3. Centrifuge tests conducted on taller slopes to further calibrate mapping procedures that were stress-dependent.
4. Experimental tests with extreme reinforcement properties to help separate the effects of strength and stiffness.
5. Experimental tests with steeper inclination angles.