1 INTRODUCTION

Soil is a relatively inexpensive and abundant construction material, which makes it ideal for use in construction. Soil is capable of providing very high strength in compression, but virtually no strength in tension. In civil engineering applications, soil usually fails in shear. Like other construction materials with limited strength, soil can be reinforced with foreign material to form a composite material that has increased shear strength and some apparent tensile strength. Metal strips, steel meshes and bar mats, geosynthetics and even bamboo have been used to reinforce soil.

The first modern-day design approach for reinforced earth structures was developed in the 1960's, by the French engineer, Henry Vidal (Das, 1984). The first reinforced earth retaining wall constructed in the United States used metallic strips for reinforcement and was completed in 1972 (Mitchell and Christopher, 1990). The construction of reinforced soil structures, including both slopes and walls, has increased considerably over the last 20 years as the advantages associated with this construction alternative are more widely recognized.

Without reinforcement, a stable slope can be constructed with an inclination angle less than or equal to the internal friction angle of the soil. Figure 1.1 illustrates how reinforcement can be added to a steeper slope to prevent the soil mass from sliding. As shown in Figure 1.1 (b), friction between the soil and the confined reinforcement keeps the reinforcement from moving during and after construction. The reinforced soil mass relies on the tension provided by the reinforcement to maintain stability at steep inclination angles. The mobilization of tensile resistance occurs once the slope experiences some deformation. For static and dynamic loading conditions, excessive deformations of a reinforced slope can occur when the reinforcement stretches, yields, breaks, or pulls out of the soil.

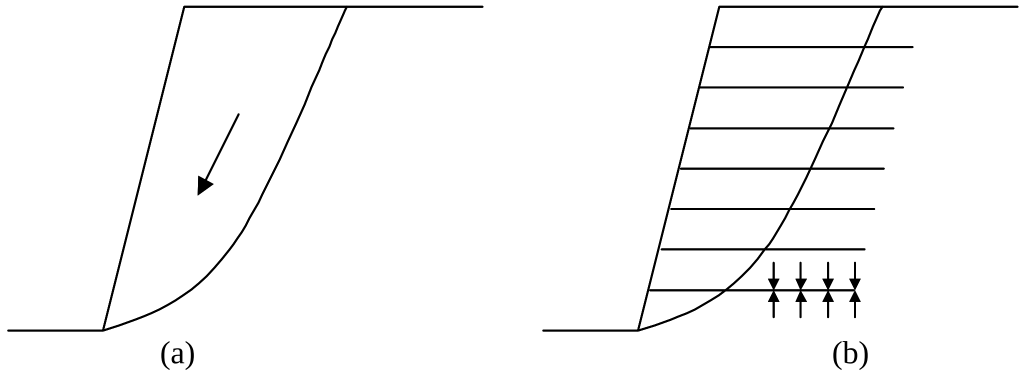

Figure 1.1 (a) Unreinforced and (b) reinforced soil slopes

Numerous methods have been developed to design reinforced soil structures for static loading conditions, but considerably fewer procedures for seismic design are available. As the number of reinforced soil structures constructed in seismically active areas of the world increases, and in response to the observed performance of existing reinforced soil structures during earthquakes, the need for development of methods capable of predicting seismically induced deformations has become increasingly apparent. Development of a practical, yet accurate, procedure has been the focus of the research described in this thesis.

1.1 MSE Walls and Slopes

Reinforced soil structures are commonly referred to as mechanically stabilized earth (MSE) structures. The soil is typically reinforced with relatively light and flexible materials, such as thin steel strips or geosynthetics, that are extensible and have high tensile strengths (Leshchinsky, 1995). The reinforcement enhances the shear strength of the soil mass by altering the pattern of the soil stresses (Clayton et al., 1993). During the construction of MSE structures, layers of reinforcement are placed within the soil backfill. Dry, cohesionless soils are predominantly used as backfill because of their high strength characteristics and because they allow drainage, thus avoiding the generation of pore pressures in the backfill.

The reinforced soil mass is typically supported by a facing that prevents raveling of the soil immediately behind the face. Depending on design and aesthetic conditions, many reinforced earth slopes typically have faces inclined at angles less than 70° and may have a geosynthetic wrapped face to prevent soil sloughing and erosion [Figure 1.2 (a)]. Reinforced earth walls can simply be considered as steeper slopes with faces inclined from 70° to 90°. The faces of reinforced soil walls may be wrapped in geosynthetics, supported by segmental or modular concrete blocks or have full-height precast panels as shown in Figure 1.2 (Holtz et al., 1997).

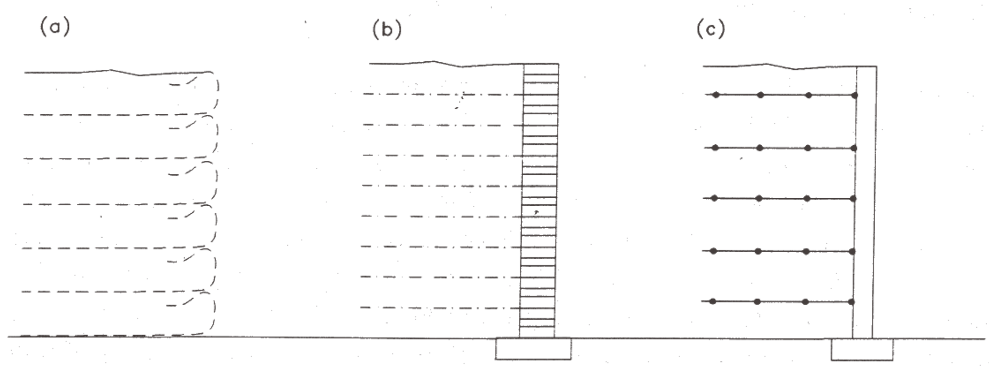

Figure 1.2 Common reinforced wall systems using geosynthetics: (a) wrap-around facing, (b) with segmental or modular concrete block, and (c) full-height precast panels (Holtz et al, 1997)

MSE structures can be constructed relatively fast and easily. Large equipment is not needed to install the reinforcement; however, proper installation by well-trained workers is extremely important. Reinforced walls and slopes are flexible and do not require a rigid foundation, thus further reducing construction costs. The reinforcement, however, may be susceptible to corrosion, creep and deterioration over time. Additional factors of safety on design are required to account for potential degradation of the reinforcement over time, which can influence material costs.

1.1.1 Geosynthetics

MSE structures reinforced with geosynthetics are called geosynthetic reinforced soil (GRS) structures. A geosynthetic, as defined by ASTM (1994), is a "planar product manufactured from a polymeric material." Geosynthetics can be used for separation, drainage-transmission, protection, filtration, fluid barriers and reinforcement. The primary role of geosynthetics in this research is as reinforcement in the soil matrix. Of the wide variety of geosynthetics available today, a principal category is that of geotextiles.

Geotextiles are permeable textile materials that can be divided into two major groups: woven and nonwoven. Monofilament, multifilament or fibrillated yarns, or slit films and tapes are woven together to create a woven geotextiles; synthetic polymer fibers or filaments are mechanically heat-bonded or needle punched to create nonwoven geotextiles. The primary function the geosynthetic determines what type of geosynthetic should be used. This research focuses on the use of geotextiles as reinforcement.

1.2 Objectives

The goal of this research was to develop a numerical model, the reinforced modified Newmark model (RMNM), capable of predicting reasonable estimates of seismically induced permanent displacements of reinforced soil slopes. This was accomplished through the following tasks:

1. The observed behavior of model reinforced slopes tested in centrifuge and shaking table tests, and analytically modeled were analyzed in order to provide insight into the behavior of reinforced slopes subjected to dynamic loading,
2. Development of a simplified model, the RMNM, that is capable of representing the primary mechanisms that cause permanent displacements in reinforced steep slopes.
3. Development of the program SPSLOPE that is capable of mapping properties of reinforced slopes to those of the model parameters, and estimating permanent displacements for an actual slope fro a particular time history.

4. Calibration and validation of the model based on the observed behavior of model reinforced slopes, as well as established principles of geotechnical engineering.

1.3 Thesis Organization

The research and its results are described in the following chapters. Chapter 2 presents published field performances of reinforced soil structures following significant earthquakes. This chapter also summarizes laboratory tests that have been conducted on model-scale slopes and walls, in order to study the behavior of the reinforcement when subjected to dynamic loading. Static and dynamic seismic design approaches used to design reinforced slopes and walls are reviewed in Chapter 3. Results of previous experimental laboratory testing using shaking table and dynamic centrifuge, conducted in conjunction with this project, are presented in Chapter 4. Chapter 5 presents the formulation and verification of the reinforced modified Newmark analysis. The model calibration, including the development and procedure, is discussed in Chapter 6. A parametric study of the seismic performance of reinforced slopes is presented in Chapter 7. Chapter 8 summarizes the results of this thesis, presents conclusions regarding the reinforced modified Newmark model and makes recommendations for further research.