CHAPTER 1. INTRODUCTION

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Across the world, many large cities have developed over low-lying, relatively flat waterfront areas underlain by weak, soft sediments deposited by rivers, lakes, or bays. In terms of make-up, these deposits typically contain soft clays and/or loose sands saturated by a high water table. Of particular concern is the safety and integrity of constructed facilities and lifelines in these areas against large earthquakes expected in the future. As illustrated by recent large earthquakes (San Francisco, CA; Kobe, Japan; and Kocaeli, Turkey), these settings are frequently the site of heavy infrastructure damage from soil failures such as excessive settlement and large lateral movements. Recent experience indicates that damage potential in these environments can be reduced using ground improvement techniques. As a result, a variety of ground modification methods are being developed to strengthen and stiffen weak soils. These techniques involve compaction, densification, drainage, replacement, adding of chemical mixtures, and other measures that increase the resistance to ground failure during shaking. Although these techniques are seeing increased acceptance, there remains a lack of performance data to confirm the effectiveness of the methods under actual earthquake loadings (current soil improvement methods for earthquake damage mitigation are based primarily on laboratory and computer studies). Field data are crucial for improving current design procedures and refining improvement techniques. The presence of a number of improved soil sites in the affected region of the recent earthquakes in Turkey provides the unique opportunity to study such sites under field conditions.

The 1999 Kocaeli Earthquake (M=7.4) struck northwestern Turkey on August 17, 1999 and caused significant damage in urban areas located along Izmit Bay. The sites that suffered the greatest damages were located primarily in areas of poorest soil conditions, typically containing soft clays and silts and/or loose, liquefiable sands. Because the affected region is heavily developed with infrastructure and there is a preponderance of poor soils, a wide range of soil improvement measures had been used to mitigate anticipated earthquake damages throughout the region. As a result, the Kocaeli Earthquake provides one of the most comprehensive and well-documented databases of the field performance of improved soil sites subjected to strong ground motions.

Following the earthquake and significant aftershocks, Virginia Tech researchers working under the auspices of the National Science Foundation traveled to Turkey to investigate the affected area to document geotechnical field performance. Primary focus of the Virginia tech team was given to investigating the performance of improved soil sites. Six improved soil sites were studied in detail. Five sites were located in industrial/commercial settings and contained mixtures of loose sands and soft clays that were treated using vibro-densification, stone columns, and/or jet grouting to increase bearing capacity and prevent liquefaction. The remaining site was a reinforced earth wall constructed of steel strips and compacted granular backfill. The sites were subjected to ground motions ranging from about 0.10g to 0.35g. The site locations ranged from 0 to 35 km from the zone of energy release. It was fortuitous that several of the sites either contained or were located adjacent to areas of unimproved soils. This allowed comparative assessments between the performance of treated and untreated ground. Preliminary observations showed that ground treatment was effective in mitigating earthquake-related damages, especially relative to damages observed at nearby sites of untreated ground.

This dissertation summarizes the results of the field reconnaissance and detailed case history analyses of two of the six sites where ground modification was used to improve the soils. The sites investigated included the Carrefour Shopping Center and Arifiye Overpass Reinforced Earth walls. Post-earthquake observations at these sites are summarized in Martin et al. (2001).

The Carrefour site is important because it provides an unprecedented case where the site was instrumented with settlement monitoring devices and the earthquake-induced settlements could be measured, and because there were improved and unimproved portions. Additionally a pair of reinforced earth walls subjected to large ground movements and strong ground shaking was investigated. The reinforced earth walls were of conventional construction and located at the site of fault rupture. The present study was undertaken to study in detail these sites, with the major issues identified below:

1. Several ground improvement techniques, including jet-grout columns, stone columns, preloading fill with wick drains, were used for a variety of different applications and soil conditions. These measures were typically undertaken to increase bearing support and/or prevent liquefaction. Overall, it was found that the ground treatment was generally effective in mitigating earthquake-induced damages, especially liquefaction related ground movements. It was fortuitous that several of the sites either contained or were located adjacent to areas of unimproved soils. This allowed comparative assessments between the performance of treated and untreated ground.

2. Post-earthquake observations show that ground improvement with jet grout columns and stone columns were effective in mitigating liquefaction related damage in sandy soils. Improved sites performed better compared to neighboring unimproved sites. Several structures on improved ground performed better than those on unimproved ground. No evidence of liquefaction was observed at improved ground sites in contrast to neighboring areas that were not improved.

3. Numerical analyses were performed to investigate the mechanisms involved in the seismic performance of soils improved by stiff columns. Commercially available program DYNAFLOW was used for these analyses. These results indicate that stiff columns carry a significant portion of the earthquake induced stresses. This significantly reduces the shear stains that develop in the improved soils therefore mitigating the risk of liquefaction.

4. The seismic performance of a pair of conventional reinforced-earth walls constructed of steel strips and compacted granular backfill is studied in detail. The walls performed well, suffering only minor damage, despite being subjected to severe ground shaking and large ground displacements. Because there are limited number of case histories regarding the seismic field performance of RE walls, the Virginia Tech

team recognized the importance of this site and documented the behavior, including measurements of wall displacements and fault-related ground movements. The subsoil conditions and construction plans for the walls were also obtained during the investigation. Numerical analyses were performed to investigate the mechanisms leading to the observed behavior. Commercially available program FLAC (Fast Lagrangian Analysis of Continua) was used for these analyses (Itasca Consulting Group 2000). The analyses were successful in predicting the observed wall behavior. The results suggest that conventionally designed reinforced earth walls perform relatively well during strong ground shaking, and that displacement may be the controlling criterion as opposed to shear failure/collapse. The study is thought to provide insight into behavior of reinforced soil structures under seismic loading and yield data that can be used to improve our predictive capabilities and design procedures. This study also reveals that such numerical techniques can be used to model seismic performance of reinforced soil structures.

5. Parametric analyses were performed using the numerical model of the Arifiye RE walls. Series of ground motions with different shaking intensities, predominant periods were used in the analyses. These studies demonstrate that permanent deformations are strongly correlated to peak velocity of ground motions. Effect of earthquake is also evident, with larger magnitude causing larger deformations compared to smaller magnitude.

6. Numerical analyses were not successful in predicting earthquake induced reinforcement forces. Earthquake induced reinforcement forces were significantly larger than those predicted by the current design methods. It was not possible to confirm the validity of the analysis results with any measurements. Due to this issue in the numerical analyses, it is essential to perform numerical analyses of centrifuge model tests. This will allow us to test the capability of the numerical analyses to predict earthquake induced reinforcement forces.

7. Reinforced soil structures perform very well in earthquakes. As discussed above reinforcement forces are much larger than those predicted by current design methods.

Therefore, good performance cannot be attributed to the conservativeness of the current design methods to estimate reinforcement forces. However, it is quite possible that the current design methods have built in conservativeness not in their predictions of reinforcement forces but in their inherent assumptions in the seismic behavior of reinforced soil structures. These studies show that performance based design should be implemented especially for seismic design of reinforced soil structures. Deformation may be the controlling factor in the seismic design of such structures.

8. Liquefaction of soils with fines was documented at several sites. These soils included soils that would not traditionally be classified as liquefiable. Liquefaction-type behavior of the soils at Carrefour site was documented in detail and studies were performed to investigate the effectiveness of Cone Penetration Testing (CPT) in characterizing and assessing the liquefaction potential of soils with fines.

The effort undertaken to address the issue identified above included a four-year effort study that involved field work, laboratory testing, and numerical analyses. In addition to initial site reconnaissance, the proposed work involved an additional trip to Turkey to collect of existing soil data where available and to perform Standard Penetration Testing (SPT), Cone Penetration Testing (CPT), in-situ shear wave velocity measurements, and laboratory index and strength testing. The balance of the effort was directed toward numerical modeling and analytical work.

This dissertation is organized to provide in Chapter 2, the information on the seismic performance of the Arifiye reinforced earth walls. Numerical analyses are described in detail and the results are presented to explain the observed behavior. Chapter 3 provides the results of a parametric study on the numerical model used in the analysis of the Arifiye reinforced earth walls. Chapter 4 gives the performance of Carrefour site and the analyses performed to investigate the unimproved and improved soils. Finally, summary and conclusions are given in Chapter 5.