CHAPTER 5. SUMMARY AND CONCLUSIONS

The 1999 Kocaeli Earthquake (M=7.4) that struck northwestern Turkey caused substantial damage in urban areas located along Izmit Bay. Widespread damage occurred in areas underlain by soft and/or loose, liquefiable alluvial sediments. In anticipation of strong ground shaking, numerous facilities and lifelines in the affected region had been mitigated using a variety of soil improvement techniques. Fortuitously, design data and construction records for a majority of these sites were available. Accordingly, these sites represent a unique and valuable database of field performance that provide crucially needed data to develop enhanced soil mitigation technologies and refine existing design approaches.

Following the Kocaeli Earthquake and significant aftershocks, Virginia Tech researchers traveled to turkey to investigate the affected area and document geotechnical field performance. Primary emphasis was upon sites where ground modification was used to improve soils. The sites ranged from 0 to 35 km from the zone of energy release, were shaken with accelerations approaching 0.40g, and encompassed a wide range of soil conditions that required a variety of ground improvement techniques to mitigate earthquake related damages. In many cases, unimproved sites immediately adjacent to treated sites and direct comparisons could be made to gauge the effectiveness of the soil treatment.

A comprehensive study of six sites was undertaken. This dissertation presents in detail, the findings from the two most instructive sites. The investigation of these sties involved field reconnaissance, field and laboratory testing of soils, seismic analysis, numerical modeling, and other analytical work. The findings indicate that soil treatment was effective in mitigating earthquake damages, especially at sites vulnerable to liquefaction or similar soil-failure phenomena. The findings from this three-year effort are presented below.

A). Findings related to the detailed study and numerical analysis of the Arifiye RE Walls, as summarized below:

1. The RE wall system at the Arifiye Bridge Overpass is an important case history that highlights the seismic performance of reinforced earth walls. The walls, constructed of steel strips and compacted select backfill, performed well despite being shaken with ground accelerations >0.2g in an M7.4 event, and being subjected to fault-related ground displacements of 350 cm that occurred almost adjacent to the wall. The structure was designed for a seismic coefficient $k_h = 0.1$. The wall was subjected to acceleration levels at least twice the design value and still maintained its structural integrity. An unreinforced earthen embankment about 250 m from the wall suffered heavy damage, settling more than 1 m.

2. Following the earthquake, the maximum permanent lateral movement of the RE facing panels was about 10-15 cm, and this occurred at about one-third the wall height above the base. The settlement along the centerline of the double-wall system was estimated at 25-30 cm, primarily due to the lateral bulging of the system.

3. The fault rupture passed through the northern abutment and the adjacent pier causing lateral offset more than 3 meters. The bridge decks collapsed due to relative movement of the piers and the bridge abutments at both sides. Bridge deck spans were simply supported.

4. Higher sections of the MSE structure settled, punching into the foundation soils. This resulted in the misalignment of several facing panels. Relative displacement of the facing panels caused them to separate and this resulted in the spillage of some backfill material.

5. The structure has undergone permanent deformations as a result of shaking. Permanent deformations may be more important in terms of serviceability of such structures. This case demonstrates that significant permanent deformations can develop before the collapse of the earth structure. However, there aren’t any methods in the design

guidelines to estimate the permanent deformations of reinforced soil structures. Permanent deformations should be a part of seismic design of reinforced soil structures.

6. Reinforced concrete bridge abutment on piles didn't suffer any damages despite the ground failure in the vicinity. The abutment didn't settle in contrast to the MSE wall it supported.

7. It was observed that the slip joints helped the wall to sustain these foundation deformations without being overstressed.

8. This case demonstrates well-designed conventionally-constructed RE walls (steel strips and compacted select fill) and with good foundations tend to perform well under strong ground shaking.

9. Analyses were performed for the as-built conditions of the wall. These results were compared with the model with different factors of safety. Reinforcement amount was increased or decreased some percentage of the as-built conditions. This is an indirect measure of the overall factor of safety of the model. Analyses were performed on these models with different reinforcement. These made possible to estimate the effect of the reinforcements used on wall performance. It was seen that the walls built with increased amounts of reinforcements performed better compared to the base case. Smaller deformations developed as the factor of safety increased.

10. The earthquake-induced RE wall deformation pattern and displacement magnitudes were successfully predicted using the computer code FLAC assuming two-dimensional, plane-strain conditions. The predicted deformation pattern was consisted of (1) significant settlement along the double-wall centerline and (2) lateral bulging with peak displacements occurring at about one-third the wall height above the base. This predicted deformation was consistent with the observations. In terms of the displacement magnitudes, a maximum lateral wall displacement of 12-14 cm was predicted, compared to an observed value of 10-15 cm. The predicted settlement along the centerline of the double-wall system was 27 cm, consistent with the observed value

of 25-30 cm. The static analysis was conducted using a Mohr-Coulomb soil model and hyperbolic soil stiffness criteria, and the dynamic analysis assumed an elasto-plastic model that assumed linear behavior up to the yield stress, and plastic behavior beyond this value.

11. Pre-earthquake stress conditions determined during a static analysis that simulated wall construction were important in terms of correctly estimating the final earthquake-induced stresses and forces in the RE system.

12. Permanent vertical and lateral displacements probably developed during the strong part of shaking (first 10 seconds), as indicated by predicted displacement time histories calculated for different locations and elevations along the walls.

13. The numerical analyses indicate that the earthquake shaking significantly increased the forces in the steel reinforcement strips, especially in the lower third of the walls. Maximum reinforcement forces reached values about two to three times those at the end of construction at the upper and lower elevations respectively. Even though these numbers indicate that the some of the steel strips reached their yield strength and some slip probably took place, the system integrity was maintained by a large margin.

14. It is interesting how the wall performed well with limited earthquake induced deformations even though the analyses show that reinforcement forces were larger than expected. The main reason these walls have not collapsed is their tolerance to deformations. Steel is a ductile material and it is believed to be the major contributor to the flexible behavior of reinforced soil structures. Strong ground shaking induces significant loads to the reinforced soil structure. But the reinforced soil structure can tolerate large deformations. Rather than withstanding against the effects of shaking like a rigid structure it deforms flexibly. If some yielding took place at some reinforcement levels, it was only temporarily. Results of the analyses show that even if some yielding and/or slip took place the deformations were not uncontrolled. Flexible nature of the structure may have been a factor in the redistribution of stresses from the yielded reinforcement levels to the other levels which can sustain more load.

15. Displacement is likely to be the controlling criterion for the seismic performance of RE walls, as opposed to shear failure or collapse. From a seismic standpoint, RE walls behave as flexible systems. In the numerical analyses, no slip surface or failure wedge developed in the backfill, although enough settlement and horizontal displacement occurred to present potential serviceability problems for the walls. Steel reinforcements have probably caused the deformations in the backfill to spread out rather than concentrating along a well-defined slip surface. Similar observations were made by Shewbridge and Sitar (1996) on tests performed on models of reinforced sand.

16. The predicted settlement presented a potential problem for the overlying roadway. Similarly, the analyses predicted that it is likely that enough out-of plane movement of the facing panels to allow backfill spillage would occur before a pronounced slip surface can develop.

17. Series of dynamic analyses have been performed using the program FLAC. Ground motions with a variety of shaking intensities and predominant periods have been applied at the base of the model and the performance of the model monitored. A total of 307 cases were analyzed. Motions within the model, permanent deformations and reinforcement forces were of primary interest. Regression analyses were performed on the results of the analyses.

18. Ground motions within the model have been investigated. It is seen that the response of the model is related to the predominant period of the applied motion. Ground motions are amplified for low levels of shaking ($pga < 0.1g$) and deamplified for higher levels. This was observed both for peak acceleration and velocity. Regression models have been developed based on the results.

19. Permanent deformations are correlated to ground motion characteristics through multivariate regression analyses. Two parameter multivariate regression models have been developed. Ground motion characteristics include peak base acceleration, peak base velocity and predominant period of the base motion. It was found that permanent deformations are strongly correlated to peak base velocity. It was seen that, when other

parameters (peak base acceleration and predominant period) were used in conjunction with peak base velocity in a regression model their contribution to the regression model was not much. Based on these observations several regression models have been developed based only on peak base velocity.

20. It was found that permanent deformations were correlated to earthquake magnitude. Larger deformations are predicted for a larger magnitude event in comparison to a smaller event with identical shaking intensity. Current guidelines do not consider magnitude in designing reinforced soil structures. This demonstrates how magnitude can be an important factor that should be incorporated to performance based design methods.

21. Numerical analyses were not successful in predicting earthquake induced reinforcement forces. Calculated reinforcement forces induced by shaking 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.

22. Results of this study are important but they are specific to the model analyzed. It is necessary to generalize the findings here to other type of mechanically stabilized earth structures. The model in this study is a double MSE wall constructed with steel strips and concrete facing panels. Seismic performance of MSE structures with other construction techniques (geosynthetic reinforcements) and different heights should be investigated in a similar parametric study.

B.) A comprehensive investigation was also performed for the Carrefour Site, and the princIpal findings from this investigation are provided:

1. The jet-grout columns used at this site were of smaller diameter (0.6 m) and installed using a faster lift rate (50 cm/min.) relative to what is typical in the US. The replacement ratio was 7% in the silty sand, and 2% in all other strata within the top 9 m. Also, the approach of using close-to-moderately spaced high-modulus columns to mitigate liquefaction at this site is distinguished from the more common approach of constructing rows of contiguous columns to form cells to contain liquefied material.

2. The application and removal of a 3.3-m thick surcharge fill in the parking garage area only moderately reduced liquefaction potential, increasing the factory of safety against liquefaction from about 0.6 to 0.7.

3. Wick drains installed in the parking garage area and Lot C (non-jet-grouted sections) did not reduce pore pressures during shaking in these low-permeability soils, but may have helped prevent surficial disruption and kept settlements more uniform during post-earthquake reconsolidation.

4. Liquefaction-type behavior occurred in ML/CL soils that were initially assessed as "non-liquefiable" based on I_c (Soil Behavior Type Index) values from CPTs approaching 3.0, and failure to meet one of the three Chinese criteria [the soil contained an average of 50% clay-sized particles (< 5μm)]. The soils appear to be similar to those also associated with documented liquefaction-type behavior in Adapazari during the Kocaeli Earthquake. The findings suggest that the Chinese criterion of percentage of clay-sized particles exceeding 15% may not be a reliable indicator of liquefaction potential in some cases. Further research is needed to better understand the behavior of such soils.

5. Subsoil conditions were investigated with an extensive array of in-situ testing. Most of the data consisted of CPT soundings. Evaluation of these soundings revealed that CPT was effective in characterizing the soil conditions. CPT results were further used to evaluate the liquefaction potential at the site for the Kocaeli Earthquake (M7.4) and a M5.8 aftershock. Current guidelines were used in assessing the liquefaction resistance. These guidelines recommend CPT unsuitable for soils with considerable

fines (I_c > 2.6). However it was shown that CPT was effective in predicting liquefaction-type behavior of these soils as well as soils with I_c < 2.6.

6. A definitive explanation for significant earthquake-induced settlements measured in a high-plasticity clay stratum (CH) in Lot C has not yet been found. It is suspected that the settlements are related to earthquake-induced strength loss and softening in these materials followed by shearing distortions due to the overlying fill. It appears unlikely that the settlements can be explained by instrument malfunction. If the suspected behavior is indeed real, then this study could indicate a previously unrecognized vulnerability of these soils.

7. Preliminary site-response analyses using higher "equivalent soil moduli" to simulate the influence of the stiffer columns (at least 100 to 200 times stiffer than the soil at this site) suggest that the high shear stiffness may have led to greatly decreased cyclic shear strains that were kept near threshold levels such that significant earthquake-induced pore pressures did not develop in the upper 9 m of the profile. Peak cyclic shear strains were estimated to have been in the range of 0.5-1% without the columns, and in the range of 0.02-0.05% with the columns.

8. Even if significant pore pressures had developed in or migrated to soils in the upper 9 m during the earthquake, as long as the jet-grout columns maintained structural integrity, their higher stiffness in vertical compression should have significantly reduced post-earthquake reconsolidation settlements relative to untreated soil.

9. The demonstrated success of the ground treatment at this site suggests that similar applications of small-diameter high-modulus columns could prove effective in cases where the soils are soft and mixed and liquefaction is of concern. Because of their high stiffness, such columns may in some cases offer added benefits over stone columns in mixed and "dirty" soils (that have low permeabilities, do not drain rapidly, and are difficult to densify), especially in terms of reducing post-earthquake reconsolidation settlements. Also, high-modulus columns of the type constructed using jet grouting can be constructed using other installation techniques, such as wet

soil mixing, that might be more economical in some cases. Thus, the findings from this study are relevant to other techniques whereby ground reinforcement using stiff columns can be achieved.

10. Finite element analyses were performed to investigate the effect of stiff column reinforcements. These analyses reveal that the soil and the stiff columns deform compatibly. Shear strains are reduced in comparison to the unimproved case and most of the shear stresses are carried by the stiff columns. This may bring an insight into the seismic behavior of soils improved with stiff columns.

11. Finite element analyses were performed to model the pore pressures for unimproved and improved ground conditions. It is seen that pore pressure development is prevented with the aid of stiff columns.

C.) Recommendations for Future Research

The findings from this study have already led to an improved understanding of the effectiveness of soil improvement measures in mitigating earthquake damages, and importantly, the data provide a basis for planned future studies that would advance existing design and analysis procedures. First, this study demonstrates that advanced numerical tools can be used effectively to model the seismic behavior of improved ground and reinforced soil structures. Further studies are necessary to implement these tools to develop versatile methods to predict performance of such structures in earthquakes. These studies should be geared towards developing generalized guidelines for seismic design of improved ground and reinforced soil structures.

Secondly, the type of numerical analyses performed on the double MSE walls can be used as a predictive tool. However it is not practical to be used as a design tool in engineering practice. More analyses are necessary to study the behavior of reinforced soil structures with different construction techniques and geometries. This will make it possible to develop generalized guidelines for the seismic design of these structures. These studies should focus on reinforced soil structures with different construction techniques and different geometries (i.e. gravity retaining type MSE walls with various heights).

Also, calculated reinforcement forces induced by shaking were significantly larger than those predicted by the current design methods. It would be useful to apply similar numerical modeling techniques to models tests where reinforcement forces as well as deformations were monitored throughout analyses. Centrifuge tests are very suitable for this type of analyses. This would make it possible to assess if numerical analyses were successful in predicting reinforcement forces.

It is also of interest how the regression models introduced in this study would apply to results of model tests in the literature. Data available in the literature can be analyzed using the regression methods described in this study. This would introduce a different approach to the already existing data. It would be informative to see the trends of the measured deformations in terms of shaking characteristics such as peak ground acceleration, peak ground velocity and predominant period of ground motion.

Finally, it was demonstrated that numerical analyses can be effectively used to investigate the seismic behavior of soils improved with stiff columns. Varying degrees of sophistication are possible. Limited testing data is available on model tests on improved ground. These tests should be studied in detail using the numerical tools introduced here. Numerical analyses should be performed on a variety of cases where stiff column reinforcements are implemented to mitigate liquefaction in sandy soils. Several cases with different reinforcing elements (stone columns, jet grout columns) with different spacings should be investigated.