4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1273

LIQUEFACTION MITIGATION USING JET-GROUT COLUMNS – 1999 KOCAELI EARTHQUAKE CASE HISTORY AND NUMERICAL MODELING

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ABSTRACT

The Kocaeli Earthquake (M=7.4) struck Turkey on August 17, 1999 and caused significant damage along Izmit Bay. Following the earthquake, the authors investigated the field performance at improved soil sites. Of particular interest was the Carrefour Shopping Center that was under construction during the earthquake. The reclaimed site is underlain by strata of saturated soft clays, silts, and liquefiable sands. Small-diameter (0.6 m) jet-grout columns 9-m long had been installed at close spacings to reduce static settlements and prevent liquefaction-related damages beneath footings and mats. Grouting had been finished for the main building which was about 60% complete when the earthquake struck. Most of the site and all neighboring sites were untreated, allowing direct comparison of seismic performance. A post-earthquake field reconnaissance found that the jet-grout-treated area suffered no settlement or ground damage; whereas the unimproved areas commonly suffered liquefaction-related settlements of 10-12 cm. To better understand the demonstrated effectiveness of the jet grouting, non-linear dynamic three-dimensional finite element analyses were conducted to model the reinforced ground at Carrefour. The results indicate that the columns probably did not reduce seismic shear stresses and strains (and thus excess pore pressures) in the soil mass. The effectiveness of the columns appears to have been more related to the vertical support they provided that prevented seismically-induced settlements. Our findings imply that design methods that assume composite shear behavior for ground reinforced with discrete elements, may over-estimate the actual level of improvement in terms of shear stress reduction in many cases. This paper presents findings of the Carrefour case history along with the numerical modeling results.

Keywords: *ground improvement, liquefaction, jet grouting*

INTRODUCTION

The Kocaeli Earthquake (M=7.4) struck northwestern Turkey on August 17, 1999 and caused significant damage in urban areas located along Izmit Bay. Following the earthquake, the authors reconnoitered the affected area to document the performance of improved soil sites. The observations showed that ground treatment was generally effective in mitigating earthquake-related damages (Martin et al. 2001). The Carrefour Shopping Center was of particular interest because the site was under construction at the time of the earthquake, and contained both improved and unimproved soil sections that could be compared in terms of seismic performance. The facility is located along Izmit Bay approximately 5 km from the ruptured fault. The estimated peak ground acceleration at the site was 0.24g (Olgun 2003).

The soil profile at Carrefour consists of recent marine sediments with alternating strata of clays, silt-clay mixtures, and loose sands. The water table is within 2 m of the ground surface. Surcharge fills and wick drains were used to improve the clays and silts, and 9 m-long jet-grout columns 0.6 m in

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diameter were installed at close spacings to provide bearing support and mitigate potential liquefaction-related damages beneath shallow foundations.

Jet grouting had been completed for the main building and the structure was about 60% complete when the earthquake struck. Grouting was just beginning in a neighboring area, and thus most of the site remained on unimproved ground. A post-earthquake field reconnaissance found stark differences between the improved and unimproved ground. The treated area suffered no measurable settlements or other forms of ground damage, whereas the unimproved sections, along with untreated building sites nearby, commonly suffered earthquake-induced settlements of up to 10-12 cm.

This paper presents the findings and numerical analyses that investigate why the ground treatment was effective. The study is instructive because the approach of using closely-spaced jet-grout columns to mitigate liquefaction differs from the common practice of constructing rows of contiguous columns to form large cells to contain liquefied material. And, although it was clear that the ground treatment was effective, our analyses suggest that the seismic behavior of the reinforced ground and the primary reason for its effectiveness was different than first thought. The reinforced ground probably did not behave as a composite soil mass, as commonly assumed by some widely-used design methods (i.e. Baez and Martin 1994). This means the dynamic shear stresses and strains in the soil were probably not significantly reduced by the reinforcement. Rather, we suspect the effectiveness was primarily related to the vertical support of the columns that reduced earthquake-induced settlements. The study has implications for the use and design of reinforced ground for seismic mitigation.

SITE LAYOUT AND SOIL CONDITIONS

The Carrefour Shopping Center is situated in a Quaternary marine setting of low ground elevation and minimal local relief (Figure 1). The relatively flat area was recently reclaimed from Izmit Bay using gravelly fills. The site is underlain by soft alluvial sediments consisting of alternating strata of soft clays, silt-clay mixtures, and silty sands. The depth to firm rock is not known, but deep geological profiles from nearby sites suggest a depth of 80 to 100 m. The water table is within 2 m of the surface. The site encompasses an area of about 55,000 m^2, as shown in Figure 2.

Representative geotechnical data (before ground improvement) are presented in Figure 3. As shown, the stratigraphy is variable, consisting of alternating strata of silt-clay mixtures, silty sands, and soft-to-medium clays. The Cone Penetration Test (CPT) tip resistances are low, and with the exception of the silty sand stratum (SP/SM), the values average about 1 MPa throughout the upper 25 m of the profile. Standard Penetration Test (SPT) $N_{1,60}$ blowcounts average 5 blows/ft. in most strata. Shear wave velocities measured by seismic CPTs are 110-140 m/sec throughout the upper 25 m.

Of concern to the designers was the potential liquefaction of the loose-to-medium SP/SM stratum found at an average depth of 6 m. This stratum varies from 2 to 4 m in thickness across the site and contains and average of 30% non-plastic fines. And although not understood at the time, the ML/CL and CH strata were also vulnerable to significant earthquake-induced deformations beneath loaded areas, as measured by site engineers; see Martin et al. (2004). The ML/CL has a PI = 10 and LL = 34, whereas the CH has a PI = 37 and LL = 66.

FOUNDATION DESIGN AND SOIL TREATMENT

The shopping center is founded on spread footings and mats. The primary design issues were large anticipated settlements the ML/CL and CH strata under static loads, and potential liquefaction of the SP/SM strata during seismic events. Jet-grout columns were installed to address both issues. Surcharge fills were also used with wick drains to treat the soils in other areas of the site. The supermarket building covers an area of 15,600 m^2, as shown in Figure 2.

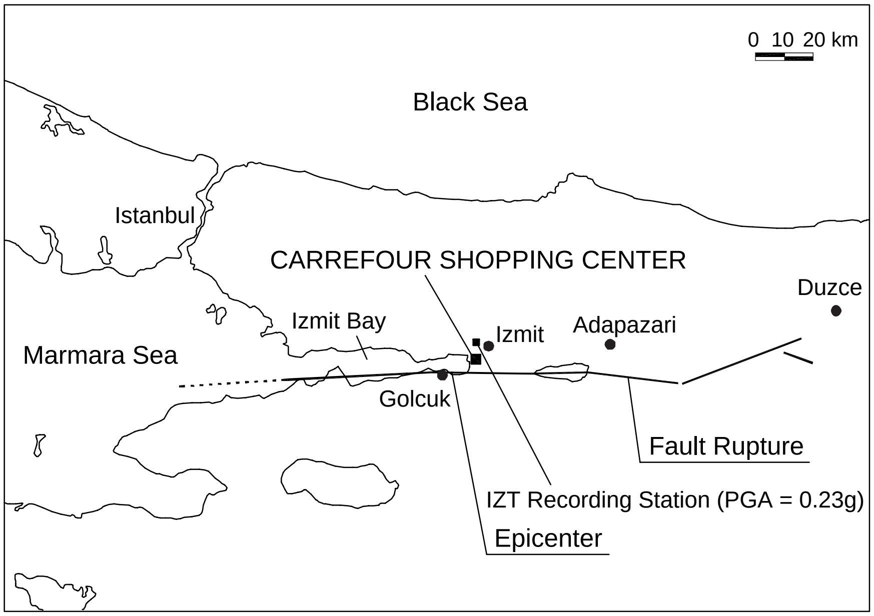

Figure 1. Map of affected area of 1999 Kocaeli Earthquake (M7.4) and location of Carrefour Shopping Center along Izmit Bay.

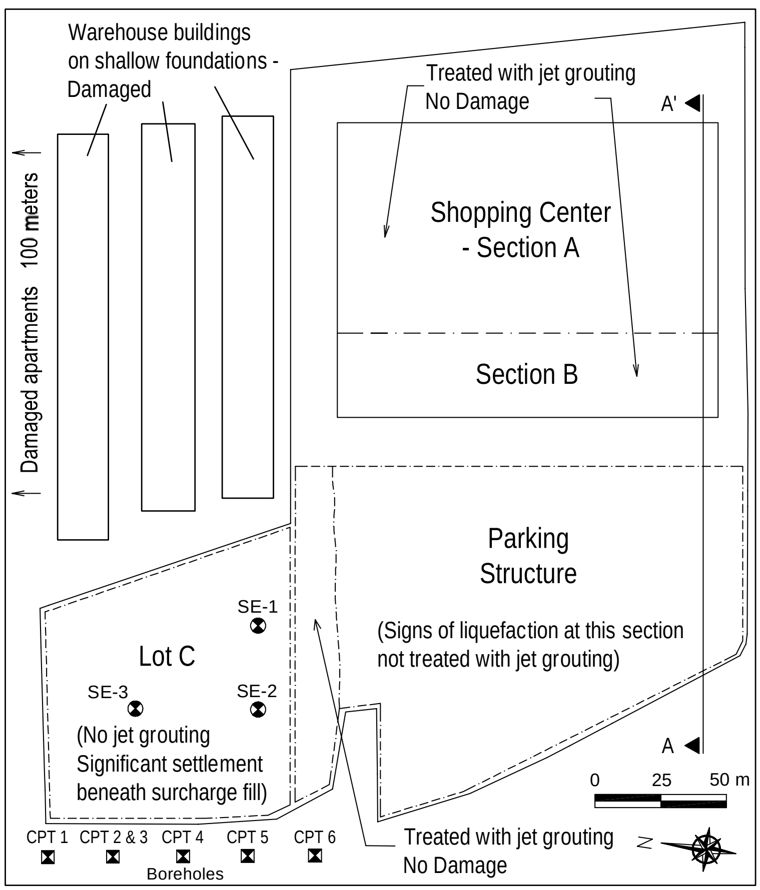

Figure 2. Site plan of Carrefour Shopping Center showing improved area and unimproved areas along with observed earthquake damages.

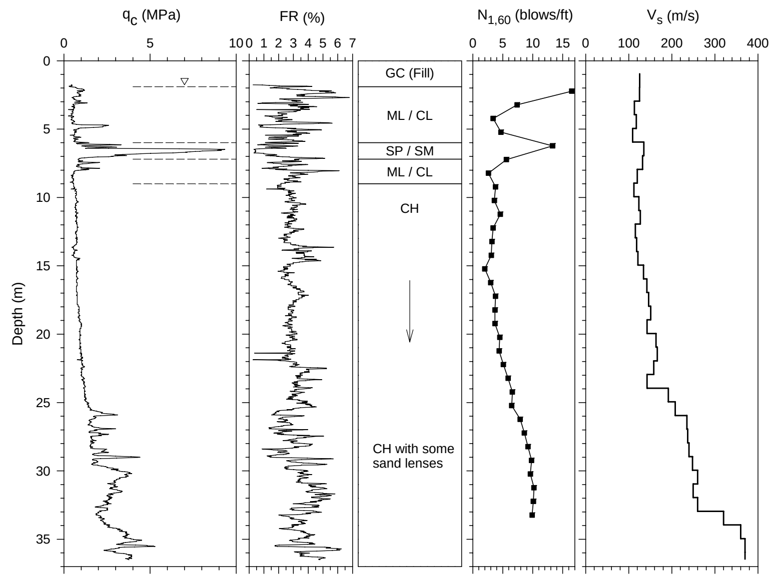

Figure 3. Typical pre-improvement geotechnical parameters from Carrefour site.

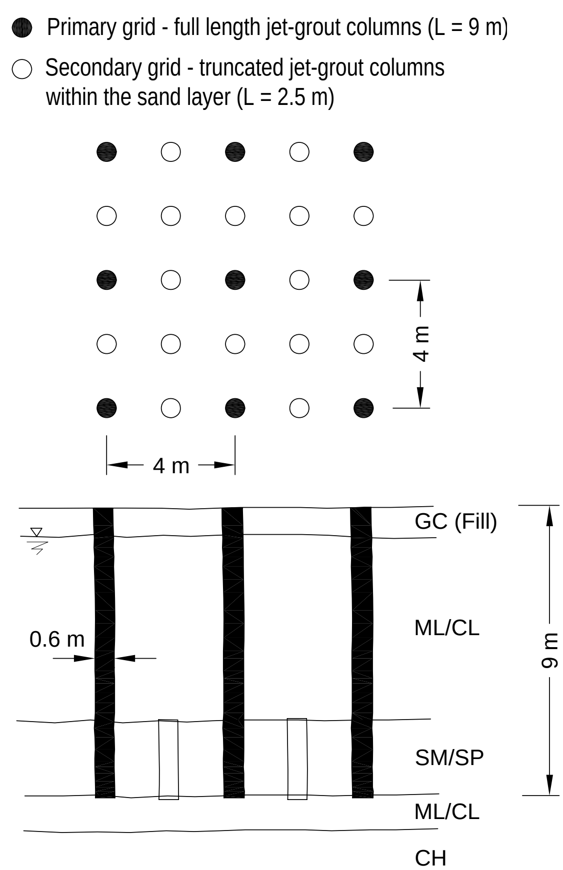

Figure 4. Typical blanket treatment used under shopping center. Area replacement in ML/CL was about 2% and 7% in the SP/SM stratum.

Section A is founded on spread footings, while Section B is supported on a mat foundation. As depicted in Figure 4, primary and secondary grids of jet-grout columns were installed to provide blanket treatment. The primary columns were 0.6 m in diameter with a center-to-center spacing of 4 m, and extended from the ground surface to a depth of 9.0 m. A secondary grid of 2.5 m-long columns was installed between the primary columns. These truncated columns, which penetrated only the SP/SM stratum, were installed with the tacit assumption that the higher jet-grout replacement in this layer would reduce liquefaction potential. In addition to the blanket treatment, groups of two and four primary columns were installed beneath the exterior and interior footings, respectively.

Section B, which rests on a mat foundation, was blanket-treated with primary columns installed at a 1.5 m center-to-center spacing. No treatment was performed outside the footprint of the building. The average area replacement ratio beneath the building was about 2% for the ML/CL stratum, and 7% for the SP/SM stratum.

The jet-grout columns were installed using a single-fluid jet-grouting system with an injection pressure of 450 bars. Neat cement at a 1:1 water/cement ratio was used as the grouting agent to form the 0.6m diameter columns. Two nozzles 2 mm in diameter were used on each rod. The rod rotation speed was 20 rpm, and the rods were lifted at the rate of 50 cm/minute. The column diameters are smaller and they are installed with faster lift rates than what is typically associated with most jet-grouting operations in the US.

Quality assurance and quality control (QA/QC) tests on the completed columns included integrity tests, pullout tests, compression strength tests on core samples, and visual field inspection. Average 7- and 28-day unconfined compressive strengths from core samples were 2.0 MPa (280 psi) and 4.8 MPa (690 psi), respectively (Emrem, 2000). These values are typical of single-fluid jet-grout columns in fine-grained soils.

PERFORMANCE DURING KOCAELI EARTHQUAKE

As mentioned earlier, during the 1999 Kocaeli Earthquake (M7.4) the shopping center was about 60% complete and was the only area that had been jet-grouted A surcharge fill was in place in Lot C. Settlements beneath the fill were being monitored each day using three extensometers installed at six elevations in the upper 25 m of the profile; see SE-1, SE-2, and SE-3 in Figure 2.

A post-earthquake field inspection showed dramatic differences in the performance of the improved section relative to the untreated areas. No settlements or signs of ground damage were found beneath the supermarket building, and construction resumed following the event. In stark contrast, significant settlements occurred in unimproved sections at the site and neighboring properties, including some level-ground areas as well as most areas that were loaded with fills or buildings, including relatively light structures.

The 3.3-m surcharge fill constituted a relatively heavy load, as did the neighboring 5- and 6-story apartment buildings; see Figure 2. The extensometers indicated 10-12 cm of earthquake-induced settlement beneath the fill, and surprisingly, much of the settlement was associated with the ML/CL and CH strata. The neighboring apartment buildings suffered settlements of similar magnitudes based on visual inspections. The level-ground parking garage section suffered estimated settlements of 8-10 cm, and water was ponded on the surface, presumably due to post-earthquake reconsolidation of the SP/SM stratum that was 4 m thick in this area. Finally, a row of three warehouses located on mat foundations about 25 m from the supermarket suffered about 5 cm of settlement. These light structures are probably similar in foundation bearing pressure to that of the partially-built supermarket.

To better gauge the effectiveness of the ground improvement, a liquefaction analysis was performed. Details are provided in Martin et al. (2004). Using the estimated PGA of 0.24g, an average FOS against liquefaction of about 0.7 is estimated for the SP/SM and ML/CL soils in the upper 10 m using the simplified approach developed by Youd et al. (2001) and Bray et al. (2004). The CH soils are considered "non-liquefiable" by these methods. Using the more recent approach recommended by Boulanger and Idriss (2006) for "clay-like" soils, and accounting for K_α beneath loaded areas such as the surcharge fill, the estimated FOS is about 0.85 for the ML/CL and CH soils in the upper 20 m.

Although there is uncertainty in the estimated strengths and cyclic resistances, it is clear that there was a significant potential for seismic failure and/or deformation in unimproved ground, as observed.

DYNAMIC NUMERICAL MODELING AND RESULTS

Although the columns were demonstrated to be effective at mitigating ground damage, the specific mechanisms were unclear. It was initially assumed that the primary benefit was the higher composite shear stiffness of the reinforced ground that reduced seismic shear stresses and strains, as suggested by Baez and Martin (1994) in their method proposed for stone columns. To investigate potential mechanisms, dynamic non-linear finite element modeling of the reinforced ground at Carrefour was performed using DYNAFLOW (Prevost 1981).

The reinforced ground, treated with 4 m x 4 m grids of primary (9 m-long) and secondary (2.5 m-long) 60 cm-diameter columns, as shown in Figure 4, was modeled in three dimensions. The finite element mesh contained approximately 22,000 elements and is shown in Figure 5. As shown, the model of the soil profile extended to a depth of 15 m. the analyses were performed with total stress analyses where pore pressure generation was not considered. Detailed soil testing data were not available at the time to calibrate the constitutive models for fully-coupled pore pressure generation behavior. Constitutive soil parameters were based on laboratory and field tests performed by the authors (Olgun 2003), and the soils were modeled to be fully non-linear during shaking using the elasto-plastic soil model developed by Prevost (1981).The jet-grout columns were modeled as structural elements with strengths and stiffnesses consistent with those measured during post-treatment field quality control tests (Emrem, 2000). To provide a benchmark for comparison, a series of runs was also performed for the case where the jet-grout columns were removed from the model such that the soil was unimproved. In terms of boundary conditions along the sides, the three-dimensional model was assumed to be surrounded by an infinitely repeating sequence of identical 4 m x 4 m reinforced soil sections. This was achieved by assigning the opposite nodes on each face of the model to be equivalent. By assigning nodal equivalency to node couples at the same elevation they share the same set of equations of motion, and therefore undergo the same motion in each direction. This equivalency imposes symmetry along each vertical face of the model. The models were shaken in two horizontal directions simultaneously using the horizontal components of the ground motions recorded in Izmit (IZT recording) during the 1999 Kocaeli Earthquake at approximately 2 km from the site. Of primary interest in the analyses was evaluating the effectiveness of the columns in reducing shear stresses and strains in the reinforced soil mass.

The analyses results are summarized in Figure 6. The figure shows the predicted peak seismic shear strains and stresses developed in the jet-grout columns and improved soil mass. For comparison, results are also shown for the unimproved soil mass. Although the stresses and strains were computed for two horizontal directions (x and y), as per the three-dimensional analyses, the results shown in the figure are the average values for both directions (average of γ_{zx} & γ_{zy}, and τ_{zx} & τ_{zy}). Also, it should be noted that the values shown for the improved and unimproved soil are representative of the average stresses and strains in the soil mass between the columns.

As can be seen on the left plot in the figure, the stiff columns were not strained as hard as the soil around them—they experienced negligible shear strains, while peak strains in the reinforced soil mass approached 1%. The analyses suggest significant strain incompatibility between the soil and columns which were about 50-100 times stiffer in shear relative to the soil. Such incompatibility was also evident in the deformed mesh shapes, which showed that the columns tended to flex back and forth within the soil profile and rotate at the ends during shaking rather than shearing along with the surrounding soil. Instead, the columns underwent mainly flexural deformations as opposed to shearing deformations. As such, they clearly did not behave as shear beams to any significant degree during shaking, as tacitly assumed. Therefore, even though the columns were much stiffer, they did not strain sufficiently in shear to attract a significant portion of the shear loading. This means the columns should not have significantly reduced shear strains, and thus excess pore pressures, in the soil mass as initially thought. As such, it can be seen in the figure that the predicted strains in the jet-grout improved soil mass were essentially equal to those in the unimproved soil.

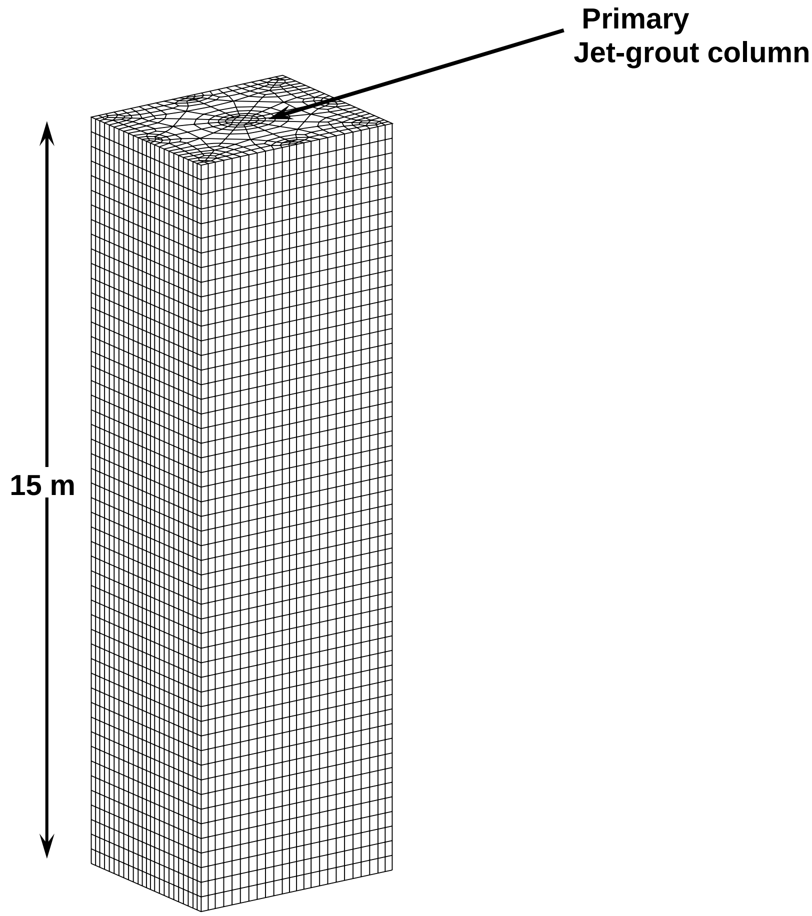

Figure 5. 3-D finite element mesh of the 4 m x 4 m jet-grout improved soil section.

Similarly, the predicted peak seismic shear stresses are shown on the right-most plot in Figure 6. The peak stresses in the jet-grout columns (~60 - 80 kPa) were consistently higher than those in the soil mass (~20 kPa), as would be expected because the columns are stiffer and attracted more load; however, they did not attract nearly enough shear stress to significantly reduce the shear stresses in the reinforced soil mass which were only slightly lower than those in the unimproved soil. Of particular significance, the stiff columns picked up only a small percentage of the shear stresses implied by area-replacement ratio methods such as Baez and Martin (1994) that assume composite shear behavior. The average shear stress reduction (shear stresses in improved soil relative to unimproved soil) that would have been expected for composite behavior at Carrefour is on the order of 80%, but as shown, the actual stress reduction was nowhere near this amount. This finding is consistent with results reported by Goughnour and Pestana (1998) based on their analysis of ground reinforced with stone columns. They found that the columns should provide little, if any, shear stress reduction in most cases. The main implication is that commonly-used design approaches based on assumptions of composite behavior for ground reinforced with discrete elements may greatly over-estimate seismic improvement (in terms of shear behavior). At the time of this writing, detailed parametric studies are being performed to better understand the effects of reinforcement stiffness, geometry and layout, end-restraint conditions, etc.

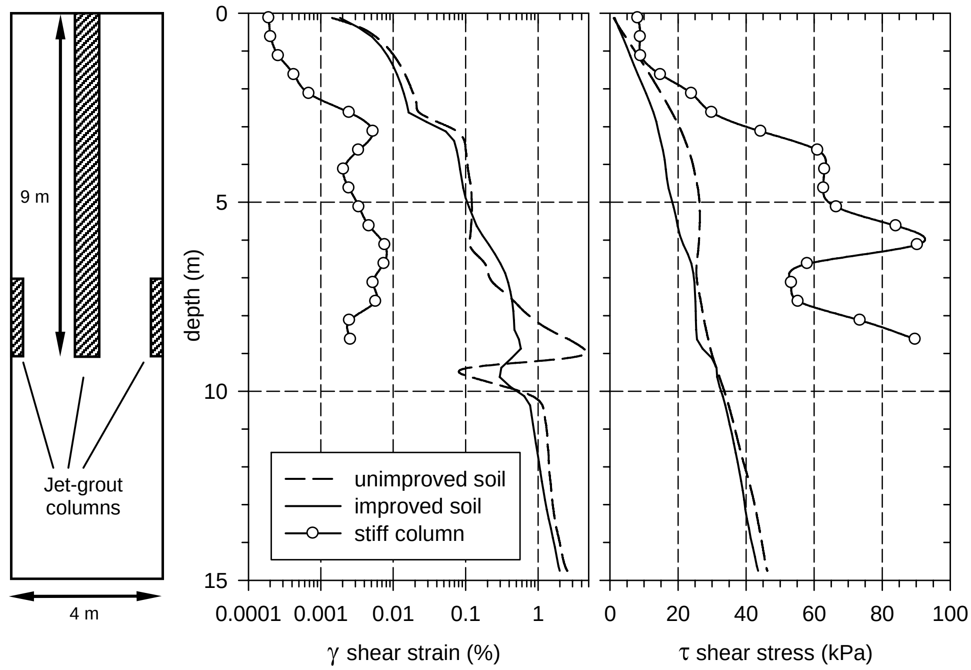

Figure 6 - Summarized results of dynamic finite element analyses of unimproved and jet-grout reinforced ground at Carrefour. Figure shows average seismic stresses and strains computed in two horizontal directions in the 3-D analyses (average of γ_{zx} & γ_{zy}, and τ_{zx} & τ_{zy}).

Interestingly, our modeling suggests that the primary contribution of the reinforcement at Carrefour was not due to seismic shear stress reduction, but rather the resulting high vertical stiffness that provided support and prevented earthquake-induced settlements in the softened soil profile. Based on our ongoing study of the site, we suspect an important and fortuitous result was that that some of the soil surrounding and/or underlying the columns did not suffer major strength loss during shaking, such that the columns maintained a significant percentage of their pre-earthquake vertical capacity. As long as their structural integrity was also maintained (i.e., no flexural failure), such reinforcing elements should have offered significant benefit in reducing seismically-induced settlements. The full-blown analyses of the site, which involve modeling pore pressure development, reconsolidation settlements in the soil profile, and other details, are beyond the scope of this paper.

SUMMARY AND CONCLUSIONS

The Carrefour Shopping Center is located along Izmit Bay in northeastern Turkey. The reclaimed area is underlain by saturated soft clays, silts, and liquefiable sands, and was subjected to strong shaking during the 1999 Kocaeli Earthquake. The estimated PGA at the site was 0.24g. The main building is founded on shallow footings and mats. Closely-spaced 0.6 m-diameter jet-grout columns were used to eliminate settlement and bearing problems in the silts and clays, and to mitigate liquefaction-related damages in the sands. The area beneath the supermarket had been treated and the building was about 60% complete when the earthquake struck. Most of the site, and all of the neighboring properties, were on unimproved ground. The seismic performance of the treated and untreated areas was compared following the earthquake. Numerical analyses were performed to better interpret the field observations. Based on the findings to date, the principal conclusions are summarized:

1. Primary and secondary grids of jet-grout columns 0.6 m in diameter were installed in tight groups beneath spread footings and at close regular spacings beneath mats foundations to mitigate liquefaction-related damages; primary and secondary columns were 9 m and 2.5 m long, respectively. This approach differs from the more common practice of constructing rows of contiguous columns to

form large "cells" to contain liquefied material. Area replacement ratios of 2% and 7% were used for the ML/CL and SP/SM strata, respectively.

2. The jet-grout-treated area beneath the supermarket suffered no damage or visible settlement, whereas significant settlements occurred in untreated sections, especially areas loaded with structures or fills. A 3.3-m surcharge fill at the site, along with neighboring 5- and 6-story apartment buildings, suffered 10-12 cm of settlement. A level-ground section in the adjacent parking garage area had water ponded on the surface following the earthquake and had settled 8-10 cm. A row of relatively light two-story warehouses located nearby suffered 5 cm of settlement.

3. Although the columns were effective in mitigating seismic damages, the primary mechanism was different than first suspected. Numerical analyses suggest that the reinforced ground did not behave as a composite soil mass due to strain incompatibility between the soil and stiff columns. The columns, about 50 to 100 times stiffer in shear, were not strained as hard as the soil around them. They experienced negligible shear strains, while peak strains in the reinforced soil mass approached 1%. Further, the analyses showed the columns and soil underwent different modes of seismic deformation. For the most part, the columns did not deform in shear and did not behave as shear beams during shaking. Instead, they behaved mainly as flexural beams and did not attract a significant portion of the seismic shear loading. The results show that the columns offered little reduction of dynamic shear stresses, strains, and excess pore pressures in the soil.

4. Of particular significance, the stiff columns caused only a small percentage of the shear stress reduction implied by area-replacement ratio methods, such as Baez and Martin (1994), that assume composite behavior. The main implication is that commonly-used design approaches based on assumptions of composite behavior for ground reinforced with discrete elements may greatly over-estimate the actual level seismic improvement (in terms of shear behavior). At the time of this writing, detailed parametric studies are being performed to better understand the effects of reinforcement stiffness, geometry and layout, end-restraint conditions, and other factors.

5. The primary benefit of the jet-grout columns at Carrefour appears to have been related to the vertical support they provided. Based on our ongoing study, we suspect that some of the soil surrounding and/or underlying the columns did not suffer major strength loss during shaking, such that the columns maintained a significant percentage of their pre-earthquake vertical capacities. As long as their structural integrity was also maintained (i.e., no flexural failure), such reinforcing elements should have offered significant benefit in reducing earthquake-related settlements.

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ACKNOWLEDGMENTS

This research was performed under the auspices of the National Science Foundation Award No. 0085281 and funding from the World Institute for Disaster Risk Management at Virginia Tech (DRM-VT). A major debt of gratitude is due to engineers and technicians at Zetas Earth Technology, Inc. in Istanbul, Turkey who served as the design engineer for this project.