High-Modulus Columns for Liquefaction Mitigation

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Abstract: This paper presents the performance of a shopping complex in Turkey where the soils were improved with jet-grout columns and preload fills and subjected to the 1999 Kocaeli Earthquake ($M=7.4$). Under construction at the time of the earthquake, the Carrefour Shopping Center covers an area of 55,000 m^2 and is founded on shallow footings, mats, and slabs-on-grade that rest on soft, saturated alluvial sediments consisting of clays, silts, and sands. High-modulus columns constructed by jet grouting were installed at close-to-moderate spacings to reduce anticipated static settlements in the clays and mitigate liquefaction in the sands. The site was subjected to a peak acceleration of approximately 0.2g during the earthquake. Grouting had been completed for about two-thirds of the site when the earthquake struck. Following the event, a field reconnaissance found stark contrast between the performance of the improved and unimproved sections. The jet-grout-treated areas suffered no apparent damage, whereas the unimproved sections of the complex, along with nearby untreated building sites, commonly suffered liquefaction-related settlements of up to 10 cm. This is the only case history known to the authors that documents the field performance of high-modulus columns used in this manner for liquefaction mitigation and direct instrumented measurement of liquefaction-induced settlements.

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Introduction

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. Peak ground accelerations of 0.35g–0.40g were measured on rock at close distances to the fault rupture. Following the earthquake and significant aftershocks, the authors investigated the affected area to document geotechnical field performance. These studies focused on improved soil sites. The observations showed that ground treatment was generally effective in mitigating earthquake-related damages, especially relative to nearby untreated sites (Martin et al. 2001).

The Carrefour Shopping Center complex was of particular importance because the site was under construction at the time of the earthquake and contained both improved and unimproved soil sections that could be directly compared in seismic performance. The complex covers approximately 55,000 m^2 and is located along Izmit Bay, as shown in Fig. 1. The site lies 8 km northeast from the earthquake epicenter and 5 km from the closest segment of the ruptured fault. Peak ground accelerations at the site were estimated at 0.24g. The soil profile consists of recent marine sediments with alternating strata of soft to medium clay, loose sands, and silts; the water table is found within 2 m of the ground surface. The soft clays and silts were improved using surcharge fills and wick drains, and small-diameter (0.6 m) high-modulus columns installed by jet-grouting were used to increase bearing support for shallow foundations and to reduce liquefaction potential of a silty sand layer that was 1–3 m thick across the site.

Jet grouting had only been completed for about two-thirds of the site when the earthquake struck. Following the earthquake, a field reconnaissance was conducted and performance comparison made between the improved and unimproved sections. Stark contrasts were observed, as the treated areas suffered no damage, whereas the unimproved sections of the complex, along with untreated building sites located nearby, commonly suffered liquefaction-related settlements of up to 10 cm.

In situ settlement measuring devices (settlement extensometers) installed at a non-jet-grouted section to monitor settlements under a surcharge fill made possible the unprecedented measurement of the earthquake-induced settlement at six elevations within the upper 25 m of the profile. As expected, significant settlements were attributed to silty sand strata, but it was surprising that comparable settlements also occurred in saturated silt/clay strata that were initially considered nonliquefiable, and for which the jet-grout columns were not designed to mitigate. Even so, the jet-grout columns were effective in mitigating liquefaction-related damages by apparently reducing cyclic shear strains and pore pressures, and minimizing post-earthquake reconsolidation settlements. This is the only performance case history known to us documenting liquefaction mitigation using jet-grout columns installed in grids as opposed to columns installed contiguously in a pattern to form enclosed cells to contain liquefiable material (O'Rourke and Goh 1997).

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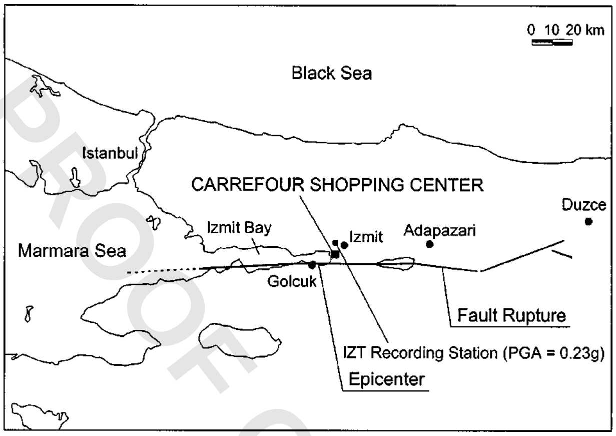

Fig. 1. Map of affected area of 1999 Kocaeli Earthquake (M7.4) and location of Carrefour Shopping Center along Izmit Bay. Note close proximity to ruptured fault and IZT seismic recording station.

Soil and Site Conditions

The Carrefour Shopping Center complex is situated along Izmit Bay in a quaternary marine setting of low ground elevation and minimal local relief (Fig. 1). The relatively flat area was recently reclaimed from Izmit Bay using sandy fills. The site is underlain by a thick stack of soft alluvial sediments consisting of alternating strata of soft clays and silty sands. The depth to firm rock is not known for this site, but deep geological profiles from other sites in the vicinity suggest a depth of 80–100 m (DSI 1977). The water table is found within 2 m of the ground surface.

As shown in Fig. 2, the site covers an area of about 55,000 m^2. A supermarket is located at the southeastern quadrant of the site, and a two-story parking garage is located at the southwestern quadrant. Both structures are supported on shallow foundations. Geotechnical field investigations for the facility included 108 cone penetration tests (CPTs), 17 standard penetration tests (SPTs), and four test pits (Zetas 1998). A suite of laboratory classification and index tests was performed as well. Collectively, data from these investigations were used for the geotechnical and seismic design of the facility, including the development of the soil improvement scheme.

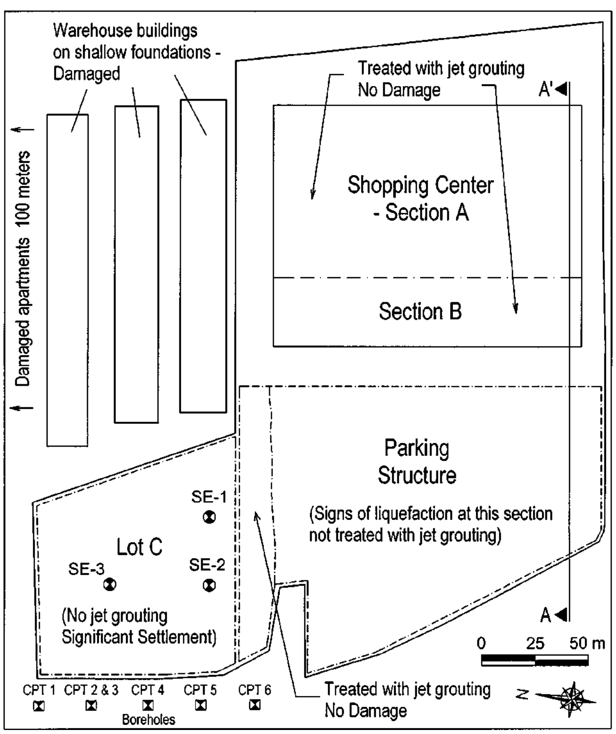

Fig. 2. Site plan of Carrefour Shopping Center showing improved area and unimproved areas along with observed earthquake damages. Locations of post-earthquake soil investigations are also indicated.

In addition to these tests, researchers from Virginia Tech conducted post-earthquake soil investigations at the site in the Fall of 2000. This work consisted of four seismic CPTs, two conventional CPTs, one SPT boring, and one exploratory Auger hole. Because the shopping center had been completed and was operational at the time, these additional tests were performed along the perimeter of the property, as shown in Fig. 2. The SPT was performed adjacent to one of the CPTs (CPT4) and samples were obtained for index testing and classification/confirmation of the soils, especially for the silty and sandy layers associated with liquefaction. Also, a borehole was drilled adjacent to the SPT, and thin-walled Shelby tubes were used to obtain continuous samples of liquefiable silty sand found at a depth of 6–9 m at this location.

The extensive array of CPT and SPT data indicated that the stratigraphy is highly variable with depth, but conditions are fairly uniform in lateral extent across the site. A typical profile and penetration test data from the site (for untreated conditions) are presented in Fig. 3. It can be seen that the CPT tip values are low, and with the exception of a 1-m-thick zone at a depth of 6 m, the values average about 1 MPa throughout the upper 20–25 m of the soil profile. SPT $N_{1,60}$ blowcounts are less than 10 blows/ft in most strata above 25 m. Shear wave velocities were measured by means of four post-earthquake seismic CPTs and indicated 110–140 m/sec for the top 10 m. A composite soil profile for the site was established from the penetration tests and is shown in Fig. 4 (see section A-A′ in Fig. 2).

As can be seen in the figure, a medium dense clayey-gravel fill (GC) overlies the entire site, extending from the ground surface to an average depth of about 3 m. The fill was placed decades prior to construction to reclaim the site from Izmit Bay. The fill varies from 2 to 4 m in thickness across the site and is thickest beneath the shopping center. The fill is located above the water table in most areas.

A soft-to-medium silt/clay stratum that extends from a depth of 3–6 m underlies the fill. Sand and gravel lenses up to 40 cm thick were encountered in this stratum in some areas. Average CPT tip resistances of 1 MPa were measured in this layer, along with shear wave velocities of 100 m/s. SPT $N_{1,60}$ values were 6 blows/ft, and the layer classifies as ML/CL. Initially, this layer was deemed "nonliquefiable" and only considered a problem from the standpoint of anticipated settlements and bearing capacity under static footing loads. As shown in Table 1, the soil contains an average of nearly 50% clay-sized particles ($<5\ \mu m$) [although 2 μm is usually considered the clay-size boundary, 5 μm is used for the Chinese criteria as suggested by Seed and Idriss (1982)]. The CPTs indicated an average soil behavior type index, I_c, of nearly 3.0. Although such soils are not normally considered liquefiable, the soils meet two of the three Chinese criteria for being suspect (percent $5\ \mu m < 15\%$, $LL < 35$, and water content $> 0.9 \times LL$); the soil contains more than 15% clay-sized particles (5 μm), but the water content is approximately equal to the liquid limit and the liquid limit (LL) is less than 35 ($LL = 33$). Similar to findings in Adapazari as reported by Bray et al. (2001), this study shows that these materials are in fact

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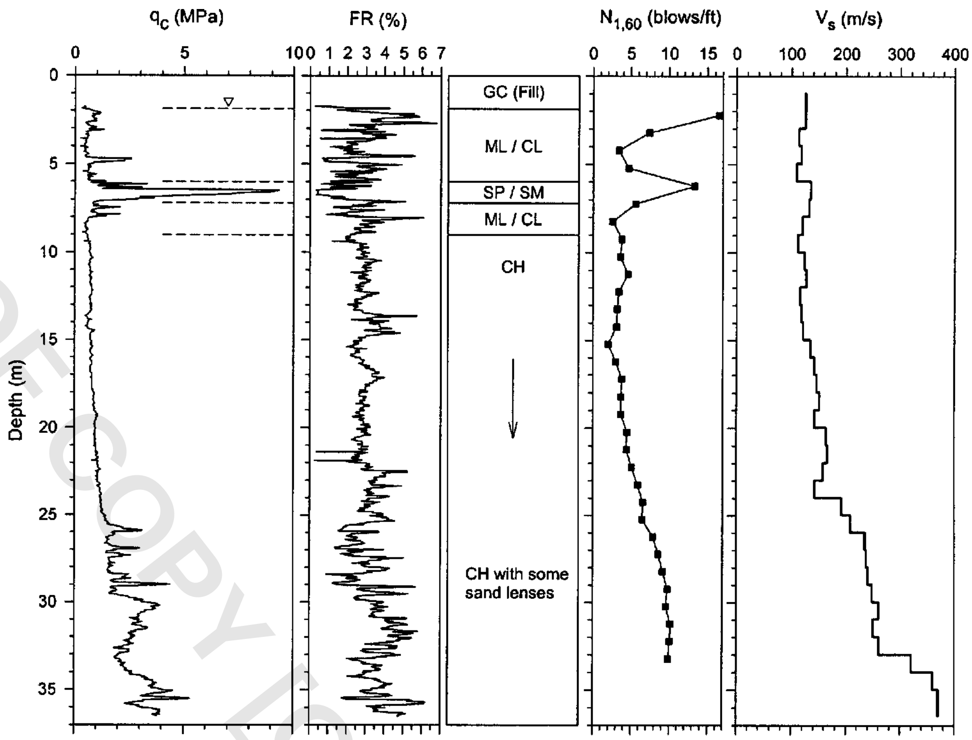

Fig. 3. Typical preimprovement geotechnical parameters from Carrefour site

susceptible to liquefaction-related effects (softening, loss of strength, settlement, etc.).

Below the clay and at an average depth of 6 m, a layer of loose-to-medium silty sand is encountered. Investigation of this layer was important because the soils were immediately identified as potentially liquefiable. Average CPT tip values are about 5 MPa, with friction ratios less than 1%. Typical SPT $N_{1,60}$ values are 13 blows/ft. Shear wave velocities in the stratum are in the range of 140 m/s. The stratum varies from 1.5 to 4 m in thickness across the site; the stratum is 2.5 m thick beneath the supermarket building, about 4 m thick beneath the parking structure, and approximately 1.5 m thick beneath Lot C. The sand contains an average of 30% nonplastic fines and classifies primarily as an SM,

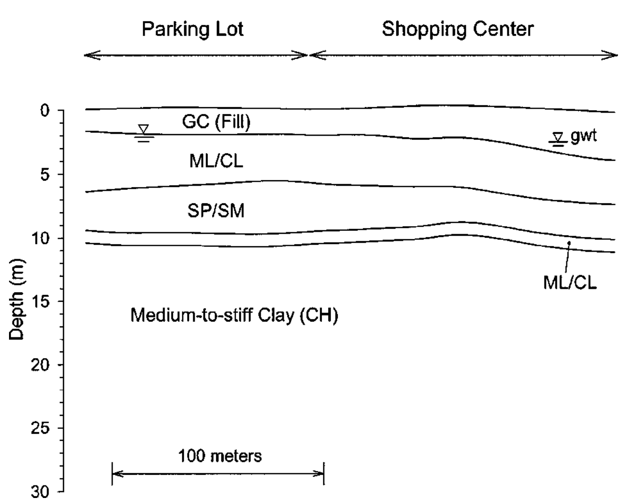

Fig. 4. Generalized soil profile through Parking Lot and Shopping Center area; see A-A′ in Fig. 2. (Note: horizontal scale is compressed.)

although there are frequent SP and SC lenses. It should be also noted that the sand contains about 15% clay-sized particles ($<5\ \mu m$) on average, but the fines are still nonplastic. Collectively, the data indicate that the sandy soil stratum would be liquefiable under moderate levels of ground shaking.

Below the silty sand layer, a 1-m-thick soft-to-medium silt/clay stratum is encountered. This stratum classifies as ML/CL and is similar to the ML/CL layer above the silty sand stratum. The soil contains 55% clay-sized particles ($<5\ \mu m$), and the water content was found to be 33%, close to its liquid limit (LL $=35\%$). CPT tip resistances of about 1 MPa were measured, and SPT $N_{1,60}$ values were 3 blows/ft.

A stratum of medium-to-stiff clay of high plasticity (LL $=60-80$ and classifies as CH) extends from a depth of 9 m to more than 35 m where the explorations were terminated. The stratum shows a gradual strength increase with depth, with CPT tip resistances increasing from 0.5 to 1.2 MPa between the depths of 9 and 25 m. The clay becomes much stiffer below 25 m, with tip values approaching 5 MPa at a depth of 35 m. Sandy lenses were commonly encountered throughout this thick stratum.

In addition to the penetration data, four post-earthquake seismic CPTs were used to measure shear wave velocities at the site. The measurements were made in an unimproved soil area about 20 m outside the property boundary west of Lot C (see Fig. 2). Fig. 3 shows a typical velocity profile. It can be seen that the profile is nearly constant versus depth for the top 25 m, with an average value of about 120 m/s. From this depth, the velocities steadily increase from 120 m/s to nearly 250 m/s over the next 10 m. A more abrupt transition occurs at a depth of about 35 m where the values increase to approximately 400 m/s and where the exploration was terminated. Overall, the velocity profile indicates a soft site that classifies as a NEHRP Site Class "F" due to the presence of liquefiable sediments, otherwise the site would classify as "E" based on the V_s-30 value of 150 m/s (IBC 2000).

Table 1. Average Grain Size and Index Test Data for Soil Strata at Carrefour Site

Depth of stratum (m)	USCS	Liquid limit (%)	PL (%)	W (%)	>no. 4 sieve (%)	<no. 200 sieve (%)	<5 μm (%)	<2 μm (%)	I_c value from cone penetration test[a]
0–3	Fill (GC)								
3–6.5	ML/CL	33	23	32	0	88	47	38	3.0
6.5–9	SM with SP, SC lenses	NP	NP	24	6	30	16	14	2.2
9–10	ML/CL	35	24	35	0	95	55	42	2.9
10–35	CH with SM, ML lenses	66	29	55	0	100	74	61	3.3

[a]I_c = soil behavior type index (Lunne et al. 1997).

Foundation Design and Soil Improvement

The shopping center and two-story parking garage are founded on shallow footings, mats, and slabs-on-grade. Details of the foundation design and soil improvement were reported earlier by Emrem (2000). The primary foundation design issues were large anticipated settlements and bearing problems in the clay, along with potential liquefaction of the silty sand layer (SM) at an average depth of between 6 and 9 m. Although not understood at the time, the ML/CL strata above and below the SM layer were also a potential source of liquefaction-related damage. Surcharge fills and wick drains were used in some sections to improve the soft clays and silts, and jet-grout columns were installed beneath the footprints of the structures in all areas to provide increased bearing support and reduced settlements in the clays and reduce liquefaction susceptibility of the sands. As discussed later, the surcharge fills probably overconsolidated the sands and silts and increased their liquefaction resistance, although this was not accounted for in the design.

The spacing and treatment depth for the jet-grout columns varied across the site due to differing soil conditions and foundation configurations. Grout column spacings, diameters, and depths for static design were selected mainly on the basis of footing size and location, and footing and slab-on-grade loads. To provide increased resistance against potential liquefaction, the designers incorporated blanket treatment beneath the building footprints using additional short jet grout columns through the sand layer. Grout column spacing details are provided in the following sections. When the earthquake occurred, jet grouting had been recently completed for the supermarket and was just beginning in the parking garage area. Thus, there were both improved and unimproved areas of the site subjected to strong ground shaking.

Supermarket Building Area

The supermarket is a one-story structure covering an area of approximately 15,600 m^2; see Fig. 2. Section A of the building is founded on isolated spread footings, while Section B is supported by a mat foundation. No surcharge fill was used for this structure because the original fill used to reclaim the site was thicker in this section and the underlying soft soils were already sufficiently strong and stiff. The only improvement was jet-grout columns, installed beneath both sections (A and B) to improve bearing support, reduce settlements of the clay, and to increase the liquefaction resistance of the underlying silty sand layer. As shown in Fig. 5, primary and secondary grids of columns were installed in rectangular patterns to provide blanket treatment. The columns in the primary grid were 0.6 m in diameter with a center-to-center spacing of 4 m. These columns extended from the ground surface to a depth of 9.0 m. The secondary grid consisted of shorter, 2.5-m-long grouted columns that were installed between the primary columns to further increase the liquefaction resistance of the silty sand stratum (about 2.5 m thick in this location). The secondary columns penetrated only the sand stratum, extending from a depth of 6.5 to 9.0 m. In addition to the primary and secondary grids, 0.6-m-diam 9-m-long columns were also installed at each spread footing location in Section A of the supermarket building. Groups of two and four jet-grout columns were installed directly beneath the exterior and interior footings, respectively. No treatment was performed outside the footprint of the building. Overall, the average area replacement ratio for the SM layer was 7%, and approximately 2% for all other layers in the upper 9 m. Grouting had been finished and the building was being constructed (about 60% complete) at the time of the earthquake.

Parking Garage Area

The soils beneath the parking garage were improved using surcharge fills, wick drains, and jet-grout columns. As shown in Fig. 2, the parking garage has a plan area of about 14,000 m^2, and the structure is founded on isolated footings with a slab-on-grade poured between the footings. The site was surcharged with a 3.3-

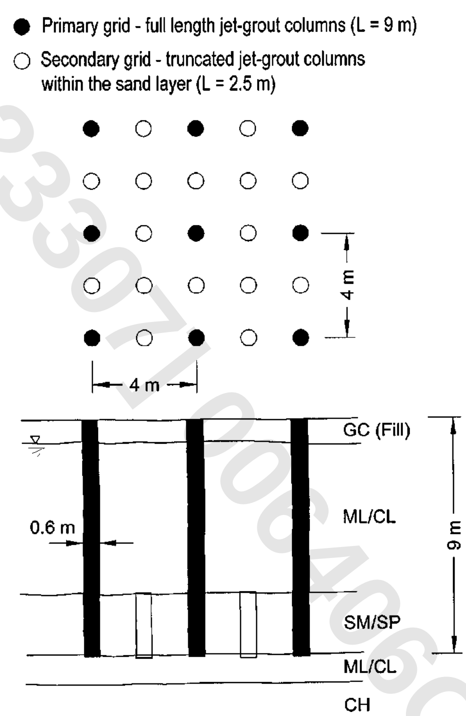

Fig. 5. Layout of jet-grout columns used for blanket treatment beneath Shopping Center building at Carrefour site. Additional columns were used at footing locations to provide additional bearing support. Average replacement ratio beneath building was about 7% in the SM layer and 2% in overlying strata.

Table 2. Construction Parameters Used for Jet-Grout Column Construction at Carrefour

Parameter	Value
Jet-grout system	Jet-1
Column diameter	60 cm
Number of nozzles	2
Nozzle size	2 mm
Rods lifting speed	50 cm/min
Rods rotation speed	20 rev/min
Injection pressure	450 bars
Water/cement ratio	1/1

m-high sand fill, and 20-m-long wick drains were installed at a 2.5-m spacing to speed up consolidation of the clay. Primary consolidation in the clay was complete and the surcharge had been removed a few weeks prior to the earthquake. The application and removal of the surcharge fill overconsolidated the near-surface silty and sandy layers to an overconsolidation ratio of 2 to 3, and increased the liquefaction resistance. Following fill removal, the area was to be blanket-treated using primary and secondary rectangular grids of jet-grout columns similar to the grouting plan for the supermarket. At the time of the earthquake, the surcharge fill had been removed and jet grouting was just beginning. Only 10% of the area had been treated, and construction of the parking garage had not yet begun.

Lot C Area

Lot C is located adjacent to the parking garage and encompasses an area of 4,160 m^2. The area is currently being used as an auxiliary parking lot. No structures were initially planned for this section, but the soils were being improved in anticipation of future development. Similar to the Parking Garage section, Lot C was surcharged with a 3.3-m-high fill, and 20-m-long wick drains were installed. Settlement extensometers were installed in three areas of Lot C to monitor settlements at several depths within the soil profile, including points located above and below the liquefiable sand layer. The surcharge fill was still in place at the time of the earthquake, and settlements were being monitored on a daily basis. Jet-grout column installation had not yet begun in this section. As discussed later in more detail, the settlement devices made possible the direct measurement of the earthquake-induced settlements of saturated strata in the upper 25 m.

Jet-Grout Column Construction

Jet-grout columns were installed at the Carrefour site 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. A summary of construction parameters used for the grouting operation is provided in Table 2. The column diameters are smaller and installation speeds faster (faster lift rates) than what is typically associated with most jet-grouting operations in the United States (Andrus and Chung 1995).

Quality assurance and quality control (QA/QC) tests on the completed columns included column 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. These values are typical of single-fluid jet-grout columns in fine-grained soils.

Expected Liquefaction Behavior of Unimproved Ground during Kocaeli Earthquake

To better gauge the effectiveness of the ground improvement and to provide more insight into the liquefaction effects observed in unimproved ground, it was necessary to perform a liquefaction analysis of the site. The analysis was primarily concerned with determining whether the observed liquefaction behavior in unimproved ground was consistent with predicted behavior, and secondly, estimating what behavior would have occurred if ground improvement had not been implemented. Of particular benefit to the analysis were the measured liquefaction-related settlements at Lot C where the soils were unimproved. These data provided unique insight into the liquefaction behavior of the soils, especially the ML/CL strata.

Ground motion recordings of the Kocaeli Earthquake (M7.4) were available from the IZT recording station in Izmit approximately 8 km from the site. The IZT site is a rock site with a V_s-30 of 800 m/s and a NEHRP classification of B (Rathje et al. 2002). These motions were used to perform a site response analysis using the *SHAKE91* computer code (Idriss and Sun 1992), and a peak ground acceleration of 0.24g was estimated for the site, close to the 0.23g peak value recorded at IZT. From this, the cyclic stress ratio (CSR) was determined for the various soil strata and the cyclic resistance ratio (CRR) values were estimated from the CPT measurements as per Youd et al. (2001). In performing the liquefaction analysis, it was recognized that the majority of the suspect soils have low CPT tip resistances and high fines contents (I_c values >2.6), a condition where the use of standard CPT liquefaction evaluation procedures can be unreliable (Seed et al. 2001). Therefore, caution and judgment were used in applying the CPT-based liquefaction procedure for these materials. Also, the highly variable and mixed conditions introduce considerable uncertainty in the prediction of field behavior. Because the liquefaction analysis was only intended to provide insight into the observed behavior and to establish general benchmarks for the effectiveness of the soil treatment toward mitigating damages, the analysis was considered appropriate for the purposes of this study.

As mentioned earlier, only the silty sand stratum (SM) that extends from a depth of 6 to 9 m in most areas was initially assessed to be liquefiable. However, post-event measurements from Lot C indicated that significant liquefaction-related settlements occurred in the ML/CL strata, and thus all of the saturated strata in the upper 11.5 m of the profile are considered susceptible to liquefaction-type behavior. Conditions near the Parking Garage are considered representative of the site and are used to illustrate typical analysis results. It can be seen in Fig. 6 that during the Kocaeli event, the site was subjected to an estimated CSR ranging from 0.15 at a depth of 1.5 m to 0.27 at a depth of 11 m.

Using CPT data, an average CRR of about 0.14 was estimated for the upper 11.5 m of the profile, as indicated by the dotted curve shown in Fig. 6. The curve accounts for the estimated fines content of each layer and is representative of conditions where no improvement was used. (The solid CRR curve shown in the figure illustrates the effect of improvement due to surcharge fills and will be discussed later.) As shown, the CSR is higher than the CRR throughout most of the profile, with the factor of safety against liquefaction ranging from about 0.5 to 0.7, and averaging about 0.6. This factor of safety typically indicates liquefaction accompanied by flow of water to the surface (sand boils) and significant settlements. Because the soil profile is mixed with pockets of sandy and clayey material and the pertinent strata vary in thickness and fines content across the site, the liquefaction is expected to be erratic. Ishihara's procedure (1985) was used to

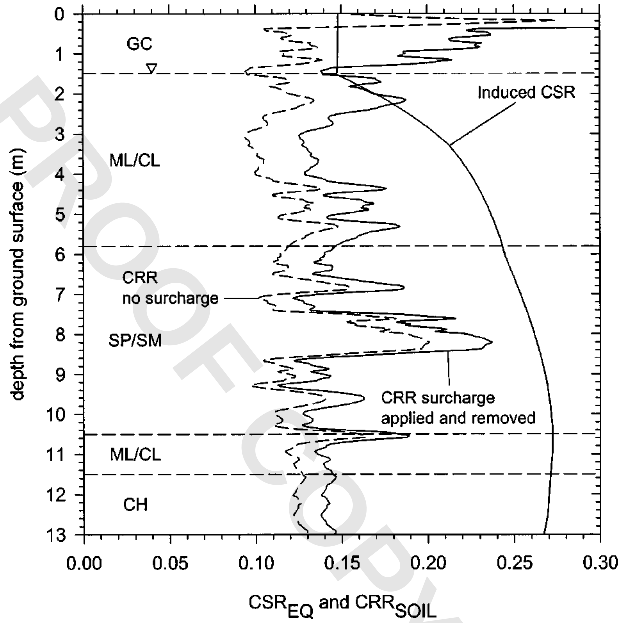

Fig. 6. Liquefaction analysis results for representative soil conditions at Carrefour site prior to jet grouting. Dotted cyclic resistance ratio curve is for nonsurcharged areas; solid curve indicates increased liquefaction resistance from OCR effects associated with 3.3-m surcharge fill application and removal in the Parking Garage area.

determine the likelihood of the liquefaction causing surficial ground damage, such as sand boils, and it was found that surface disruption was not likely unless it was assumed that significant liquefaction (in the conventional sense) occurred in the ML/CL strata. Also, no significant lateral movements are expected for this level-ground site.

Finally, it was necessary to predict the liquefaction-induced settlements in unimproved ground across the site. Although the Ishihara and Yoshimine (1992) method could be used to predict settlements of the SM and SM/SP strata, this method is not directly applicable to the ML/CL soils prevalent at the site. Moreover, the measured settlements in Lot C (unimproved) allowed back-calculations of the apparent earthquake-induced volumetric strains associated with specific soil strata in the upper 25 m of the profile. These strain data, which averaged close to 1.0% in the upper 9 m, were used to predict the settlements of unimproved soil strata at other areas of the site and surrounding properties. Based on the range of thicknesses of the relevant strata, the predicted settlements in unimproved ground are on the order of 7–11 cm for the Parking Garage section and 6–10 cm for the Supermarket area. These are probably upper-bound settlement predictions for nonloaded areas because the measured settlements/strains in Lot C could have been due in part to constant-volume shearing distortions induced by the overlying surcharge fill, as opposed to pure volumetric straining; see later discussion.

Soil conditions beneath nearby vacant lots and building sites are thought to be similar to those at the shopping center complex. In particular, it is believed that the ML/CL and SM strata underlie much of the surrounding area. Three warehouses are located adjacent to the shopping center building and a set of six-story apartments is located approximately 100 m from the northern boundary of the site. Both facilities are founded on shallow footings and unimproved soil. The expected liquefaction and settlement potential at these untreated neighboring sites are assumed to be similar to those of the untreated areas at the shopping complex, and thus the expected factors of safety against liquefaction and settlements are assumed to fall somewhere in the range of 0.6–0.7 and 7–12 cm, respectively (the range of values estimated/observed for the Carrefour site). Although rough, these estimates still provide an additional benchmark for performance comparisons between treated and untreated ground. A summary of the expected liquefaction behavior of untreated soils is presented in Table 3.

Field Performance during M7.4 Kocaeli Earthquake

As discussed earlier, peak ground accelerations during the Kocaeli Earthquake (M7.4) are estimated at 0.24g for the site. The morning following the event, the grouting contractor and site en-

Table 3. Summary of Apparent Effectiveness of Soil Treatment During Earthquake

Section	Treatment used[a]	Predicted behavior without treatment	Observed behavior	Apparent effectiveness of treatment
Supermarket building (60% complete)	Jet-grout columns with replacementratio of 7% in silty sand and 2% in other layers.	F.S.$_{Liq'n}\sim 0.6$ Sand boils not likely. $\Delta H \approx 6-10$ cm	No structural or ground damage. No sand boils or settlements.	Prevented liquefaction-related damages; reduced cyclic shear strains, prevented pore pressure build up.
Parking garage	Surcharge fill 3.3-m thick applied and removed. Wick drains installed. Only 10% of area jet-grouted.	F.S.$_{Liq'n}\sim 0.7$ Sand boils not likely. $\Delta H \approx 7-10$ cm	Settlements of 7–10 cm (estimated). No sand boils.	Surcharge fills slightly increased liquefaction resistance. Wicks did not reduce pore pressures during shaking, but may have helped prevent sand boils.
Lot C	Wick drains installed. Surcharge fill 3.3-m thick in place during earthquake. No jet grouting.	F.S.$_{Liq'n}\sim 0.75$ (beneath fill) Sand boils not likely. ΔH measured, prediction not needed	Settlements of 10–12 cm measured. No sand boils.	Wicks may have helped prevent sand boils and nonuniform settlements during post-earthquake reconsolidation.
Adjacent warehouses and apartment buildings	None.	F.S.$_{Liq'n}\sim 0.6-0.7$[b] $\Delta H \approx 7-12$ cm[b] (assumed)	Settlements of 5–10 cm common beneath structures. No sand boils.	

[a]At time of Kocaeli Earthquake.

[b]Assuming soil conditions are similar to those beneath Carrefour site.

gineers conducted a site reconnaissance of the shopping complex that included a field inspection, with photographs and documentation, and reading of settlement monitoring devices that had been recently installed in Lot C (Zetas 1999). Virginia Tech personnel visited the site several days later and conducted follow-up inspections of the site, as well as other building sites located nearby. The findings allowed the rare opportunity to make performance comparisons among sites that were in different stages of improvement.

Supermarket Building—(Jet Grouting⇒No Damage)

At the time of the earthquake, the foundations had been poured and a steel framework erected for the supermarket building. It may be remembered that no preload was used in this section nor were wick drains installed. Post-earthquake field inspections found no structural damage in the building, and no sand boils or liquefaction-related effects, such as settlements, were found at the building or in the surrounding lot. The area was visibly unchanged by the event, and construction of the building continued as scheduled with no repairs necessary. As discussed earlier, liquefaction was predicted for this section if left unimproved ($F.S._{Liq'n} \approx 0.6$), with the primary anticipated damage being liquefaction-induced settlements of approximately 6–10 cm. The lack of structural or liquefaction-related damage suggests the jet-grout columns effectively mitigated the anticipated effects.

It is believed that a main reason the columns were effective is that they introduced considerable shear stiffness and reduced earthquake-induced peak shear strains to levels below which significant pore pressures did not develop. To investigate this idea, the authors performed two simple one-dimensional site response analyses of the soil profile, one with and one without the estimated influence of the columns, and the results were compared. The Kocaeli time history recorded at the nearby IZT station was used as input into *DYNAFLOW* (Prevost 2002) for these analyses. The first site response analysis was performed using the shear moduli of the untreated soil based on the measured shear wave velocities. For this case, the peak shear strains calculated for the strata in the upper 9 m of the profile were about 1%. Then, as a simple first-order approach, the influence of the stiff columns was simulated by assigning higher ‘‘equivalent shear moduli’’ to each improved layer based on the area and stiffness ratios (the columns were at least 50 to 60 times stiffer in shear than the soil). A second site response analysis was then run, and the calculated peak strains fell within the range of 0.01–0.02%, two orders of magnitude lower than for the untreated case. The threshold shear strain required for initiation of pore pressure development was not determined for these soils, but this value is typically in the range of 0.01% for other sands (Dobry et al. 1982). Thus, although the analysis was simple, the findings suggest that column stiffness may have played a major role in mitigating liquefaction damage by inhibiting pore pressure development in the upper 9 m during the Kocaeli event. Detailed numerical studies using a more robust model are needed to further investigate this issue.

The possibility must also be considered that liquefaction, or at least significant pore pressure development, could have occurred in the soils beneath the shopping center, but the jet-grout columns provided sufficient support to prevent settlements. The absence of sand boils in this area does not necessarily indicate that liquefaction did not occur because the capping layer is too thick and the liquefiable layer too thin to cause surficial ground disruption. (Although the ML/CL and/or CH materials apparently suffered strength loss and softening beneath the fill in Lot C, it is not believed that these fine-grained materials would ‘‘liquefy’’ in a manner that would readily produce sand boils.)

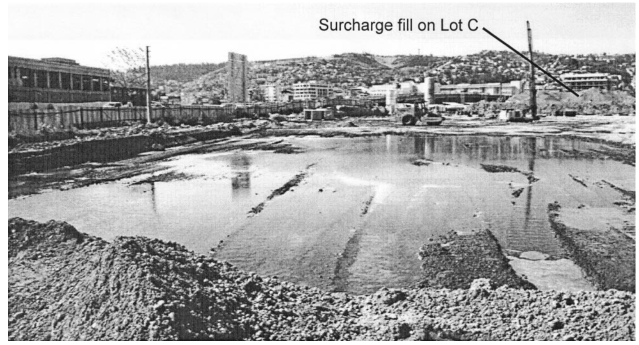

Fig. 7. Ponding of water (7–10 cm deep) at untreated portions of parking structure that was expelled through wick drains following M7.4 Kocaeli Earthquake. Lot C, under surcharge fill, is visible at right rear of inundated area. Photograph taken the morning after the event.

Parking Structure Area—(Surcharge Fill, Wick Drains, No Jet Grouting⇒Liquefaction-Related Settlements)

The parking structure had not yet been built and jet-grout column installation was just beginning in this section when the earthquake occurred. Wick drains had been installed and the area surcharged with a 3.3-m-high fill that had been removed a few weeks before the earthquake. In contrast to the supermarket area, significant settlements occurred in this section. Site personnel reported that the nongrouted portion of the parking structure area was inundated with 7–10 cm of water that ponded on the ground surface the morning after the earthquake, as shown in Fig. 7. During field reconnaissance, it became apparent that the water originated from the underlying soil deposit via drainage through the wicks. The magnitude of the settlement should have equaled the depth of water ponding on the surface, as the amount of expelled water is expected to be reflective of the earthquake-induced volumetric change that occurred in the soil profile. The fairly uniform depth of water suggests the settlement was uniform. No sand boils were observed anywhere in the area.

In interpreting the observed behavior, it is important to consider the possible effects of the surcharge fills and the wick drains on the liquefaction behavior. The surcharge overconsolidated the sandy and silty layers to an overconsolidation ratio of 2 to 3. From this, we estimated the corresponding increase in liquefaction resistance using the approach presented in Salgado et al. (1997). As shown in Fig. 6, only a modest increase in factor of safety is predicted, from 0.6 without the fill to slightly more than 0.7 with the fill. Thus, the surcharge fills apparently played only a minor role in reducing the liquefaction susceptibility of the sand stratum.

It is not clear what role the wick drains played in the observed behavior. It was initially thought that the wick drains may have helped prevent liquefaction, as defined by $r_u = 100\%$, by providing partial drainage during the event. But a preliminary analysis [as per the basic approach outlined in Seed and Booker (1977) and Mesri and Shahien (2001)] that considered the soil permeability, drain spacing (2.5 m), and flow capacity of the drains, indicates that the flow capacity of the wicks was many orders of magnitude too low to have been effective in preventing significant

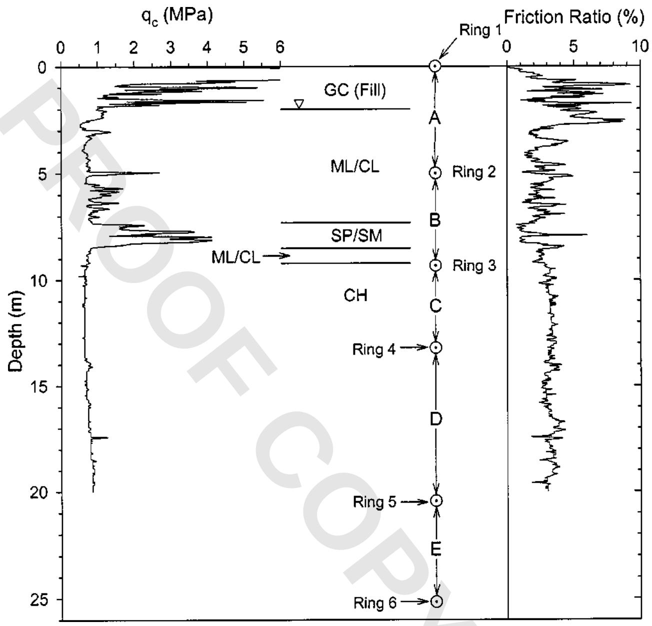

Fig. 8. Soil conditions near SE2 in Lot C (unimproved soils) where settlements were measured. Fig. shows positions of settlement rings, soil layers A–E, and CPT results.

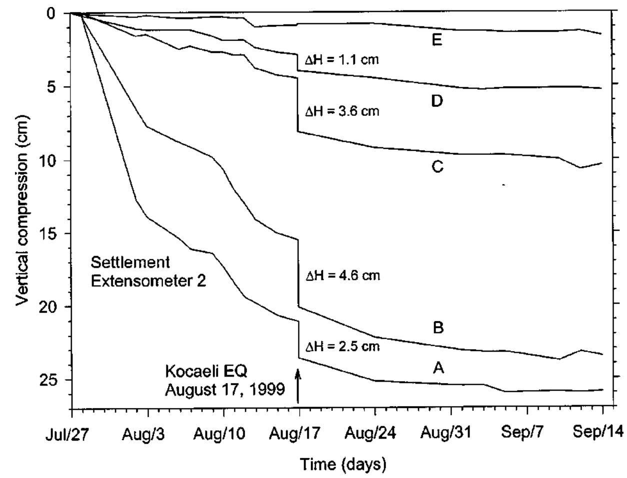

Fig. 9. Settlement versus time for Layers A–E (shown in Fig. 8) under surcharge fill in Lot C. Note abrupt offset in curve on 17 August 1999 that indicates settlement induced by Kocaeli Earthquake (ΔH values).

pore pressure buildup during shaking in these low-permeability soils. It was also initially thought that the drains helped to prevent surface disruption by providing a controlled drainage path during reconsolidation of the sand stratum (i.e., no sand boils formed although significant settlements occurred). Prevention of sand boils would have also kept the settlements more uniform. While the drains may have been effective in this regard, the level of effectiveness is somewhat moot because Ishihara's relationship predicted that soil boils were unlikely to occur in this section.

Lot C Area—(Wick Drains, No Jet Grouting⇒Liquefaction-Related Settlements)

Similar to the parking garage area, Lot C was surcharged with 3.3 m of fill and wick drains were installed. The fill was still in place at the time of the earthquake (see fill in background of photograph in Fig. 7). To monitor settlements in the clayey soils due to the fill, settlement extensometers were installed at three locations in Lot C (SE1, SE2, SE3 in Fig. 2). The extensometers consisted of plastic guide pipes 5 cm in diameter with a set of magnetic rings that slid down along the outside of the fixed-in-place pipes as the soil profile settled. The positions of the magnetic rings were measured daily to determine the settlement at specific elevations within the soil profile. It is fortuitous that these devices were in place during the earthquake. Fig. 8 shows the elevations of the six settlement rings installed at SE2, and Fig. 9 shows the measured settlement versus time. The behavior at this location is representative of that observed at the other extensometers.

Of particular importance is the sudden offset in the curves following the Kocaeli Earthquake on August 17, 1999. By comparing pre- and post-earthquake readings, the settlements associated with the earthquake could be estimated for each ring location. And by subtracting the settlement of a given ring from that of the ring located immediately above, the settlement attributed to the portion of the soil profile situated between the two rings could be obtained. As such, the profile was divided into five sections (layers A though E) and the earthquake-induced settlement of each layer is noted in Fig. 9. The earthquake-induced settlements indicated in the figure occurred in less than 24 h, the elapsed time between the reading of the instruments the day before and morning after the earthquake. As can be seen, the total earthquake-induced settlement of Lot C was about 12 cm, and it was surprising that a significant percentage of the settlement was attributed to the clayey and silty strata. Layer A, which contains 2 m of medium dense unsaturated fill (GC) and 3 m of soft saturated ML/CL material, experienced a settlement of 2.5 cm. The gravelly fill is not believed to have contributed significantly to the measured settlements. Layer B contains 1.5 m of cleaner SM material and 3 m of the ML/CL soil. The measured settlement in this layer was 3.5 cm. The average apparent volumetric strain in these upper layers was about 0.8%. Unexpectedly, the balance of the settlement, nearly 6 cm, was associated with the underlying materials classified as CH (layers C, D, and E) and reaching to a depth of more than 20 m, especially layer C, which underwent 3.6 cm of settlement (apparent volumetric strain of 0.9%). A definitive explanation as to how these fine-grained soils could have experienced such rapid settlements cannot be given at this time. It is suspected that the settlements are due to earthquake-induced strength loss/softening and subsequent constant-volume shearing distortions due to the overlying fill. It is possible, too, that the instruments malfunctioned and some of the settlement readings were in error; however, we have not yet been able to conceive of how any such malfunctions could have occurred.

To our knowledge, this type of earthquake-induced settlement measurement was not possible previously, and provides a unique opportunity to better understand the behavior of these soils under strong ground shaking. The observations are also important, first, because apparent liquefaction-type behavior was demonstrated for an ML/CL material that was considered "nonliquefiable" by virtue of I_c values >2.6 from the CPT and failure to meet the Chinese criteria by virtue of a clay-sized fraction greater than 15%. Thus, clay-sized fraction and I_c values may not be appropriate indicators of liquefaction potential in some cases. Secondly, although further study is needed, it appears that the CH materials were also susceptible to at least some percentage of strength loss and softening under strong ground shaking—an unexpected and surprising possibility.

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Finally, the surcharge fill was still in place and would have masked any surficial ground disruption; however, no sand boils were found on the ground surface along the edges of the filled area. The wick drains are thought to have drained water from the underlying deposit due to earthquake-induced excess pore pressure development, similar to what occurred in the parking garage, but the fill prevented direct observation of expelled water. The liquefaction behavior of these materials is the subject of ongoing detailed study by the writers.

Other Building Sites Nearby (No Soil Treatment⇒Settlements and Damage)

To provide additional performance comparisons between treated and untreated ground, properties adjacent to the shopping center site were reconnoitered following the earthquake. Based on soil borings and CPTs in this general area, it is probable that the ML/CL and SM strata underlying the shopping center also underlie the surrounding sites. Liquefaction-related effects were common in unimproved soils in the immediate vicinity. Based on visual inspection by Virginia Tech personnel, the apartment buildings across the street commonly settled 5–10 cm, and the warehouses just outside the property boundary settled about 5 cm. No sand boils were observed at either of these locations. For the most part, the underlying soils appeared to develop pore pressures, soften, and settle beneath the structures, but did not exhibit the liquefaction behavior normally associated with cleaner sands.

Discussion of Soil Improvement Effectiveness

As shown in Table 3, the comparison of field behavior among the treated and untreated areas was used to gauge the effectiveness of soil treatment in mitigating earthquake-related damages. Although the presence of fine-grained soils and highly variable conditions complicated the liquefaction analysis, the behavior observed at the unimproved sections of the shopping complex and adjacent building sites was reasonably consistent with what was predicted for the Kocaeli Earthquake loading. More importantly, there was a clear distinction between the earthquake-related damage in the untreated areas and the lack of damage in the jet-grouted section. It is believed that the stiff close-to-moderately-spaced columns reduced shear strains and restricted pore pressure development in the upper 9 m of the soil profile. In fact, the columns may have been more effective than initially credited because only the 3-m-thick SM stratum was considered liquefiable during design, and only this layer was treated during secondary grouting; however, measurements from Lot C indicate that all saturated strata in the upper 9 m of the profile contributed to earthquake-related settlements, especially the ML/CL strata. Even if significant pore pressures had developed in or migrated to the upper soils during the earthquake, as long as the jet-grout columns maintained structural integrity, their higher stiffness should have significantly reduced post-earthquake reconsolidation settlements.

As mentioned earlier, the jet-grout columns used for this project were of smaller diameter (0.6 m) and constructed using a faster installation procedure relative to most U.S. jet grouting operations. The replacement ratio was about 7% in the lower SM stratum, and 2% in the ML/CL strata located above and below this layer. Also, the liquefaction mitigation approach used for this project is distinguished from the more common encapsulation approach of constructing rows of contiguous columns to form cells to contain liquefied material (i.e., Welsh and Burke 1991; O'Rourke and Goh 1997). The success of the ground treatment at this site suggests that similar applications of small-diameter high-modulus columns could prove useful at other sites where the soils are soft and mixed and liquefaction is of concern.

Of particular importance, the writers suspect that high-modulus columns may in some cases offer added benefits over stone columns in mixed and "dirty" soils that have low permeabilities (and do not drain rapidly) and are difficult to densify, especially in terms of reducing post-earthquake reconsolidation settlements. Also, jet-grout column installation does not densify the surrounding ground, as the improvement is solely from the strength and stiffness of the columns (and/or encapsulation of the liquefied material in cases where this approach is used). As a result, jet grouting can be used in situations where densification of the surrounding ground is not desirable owing to the need to avoid settlement during installation. It is also important to note that high-modulus columns of the type constructed using jet grouting can also be constructed using other installation techniques that might be more economical in some cases, such as wet soil mixing. Thus, the demonstrated effectiveness of the jet-grout columns at this site has relevance to other techniques whereby ground reinforcement via stiff columns can be achieved.

The application and removal of surcharge fills probably had only a minor effect on increasing the liquefaction resistance of the soils. Also, the wick drains probably did not play a significant role in reducing pore pressures during shaking, but may have helped prevent surficial ground disruption and/or contribute to settlements being more uniform. Finally, the surprising liquefaction-type behavior of the ML/CL soils, and apparently the CH materials, underscores the need for further research on these materials.

Summary and Conclusions

The Carrefour Shopping Center, a 55,000-m^2 complex in Izmit, Turkey, was being built at the time of the M7.4 Kocaeli Earthquake on August 17, 1999. Estimated peak ground accelerations during the earthquake were 0.24g. Soft and liquefiable saturated alluvial sediments underlie the site, and the structures are supported on shallow footings and mats. Soft clays and silts had been improved using surcharge fills and wick drains, and small-diameter (0.6 m) high-modulus jet-grout columns were used to increase bearing support for shallow foundations and reduce the liquefaction potential of a 3-m-thick silty sand layer. The main shopping center building was partially built, and only the area beneath the footprint of the building and a small portion of the parking garage had been jet-grouted when the earthquake struck. Post-earthquake field reconnaissance, along with settlement monitoring devices installed in adjacent Lot C, made possible the performance comparison between jet-grouted sections and adjacent untreated areas. The jet-grout-treated sections showed no damage, but the untreated areas of the site, along with other nearby untreated sites, commonly experienced settlements of 10–12 cm. The jet-grout columns were effective in reducing liquefaction-related damages in the treated areas.

A number of important points are summarized:

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 United States. 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.

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2. The application and removal of a 3.3-m-thick surcharge fill in the parking garage area only moderately reduced the liquefaction potential, increasing the factor 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 ''nonliquefiable'' 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 (<5 μm)]. 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. 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.
6. Preliminary site-response analyses using higher ''equivalent soil moduli'' to simulate the influence of the stiffer columns (at least 50 to 60 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 1% without the columns and in the range of 0.02% with the columns.
7. 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.
8. 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.

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