

# PRELIMINARY FINDINGS FROM AN INVESTIGATION OF IMPROVED GROUND PERFORMANCE DURING THE 1999 TURKEY EARTHQUAKES

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## Abstract

Ground improvement by various methods has been used to reduce the potential for liquefaction-related damages in sandy soils and settlement-related problems in soft clays; however, there remains a need for more field performance data for improved ground during earthquakes. Field case history data are crucial to assess our current predictive capability and refine existing design procedures. Following the August 1999 Kocaeli, Turkey Earthquake (M7.4) and significant aftershocks, the authors investigated the affected area to document geotechnical field performance. These studies focused on investigating improved soil sites. The investigated sites represented a range of soil conditions and improvement techniques. The sites were located primarily in industrial/commercial settings and typically contained loose sands and soft clays that were treated using preloading, vibro-densification, stone columns, and/or jet-grouting to increase bearing capacity and prevent liquefaction. Ground motions ranged from about 0.10g to 0.35g among the sites that were located from 0 to 35 km from the zone of energy release. Preliminary observations showed that ground treatment was effective in mitigating earthquake-related damages, especially relative to damages observed at nearby sites of untreated ground. Detailed study of the sites, including parametric numerical analyses, is just beginning.

## Introduction

The 1999 Kocaeli Earthquake (M=7.4) struck northwestern Turkey and caused significant damage in urban areas located along Izmit Bay. Following the earthquake and significant aftershocks, the authors investigated the affected area to document geotechnical field performance. These studies focused on improved soil sites.

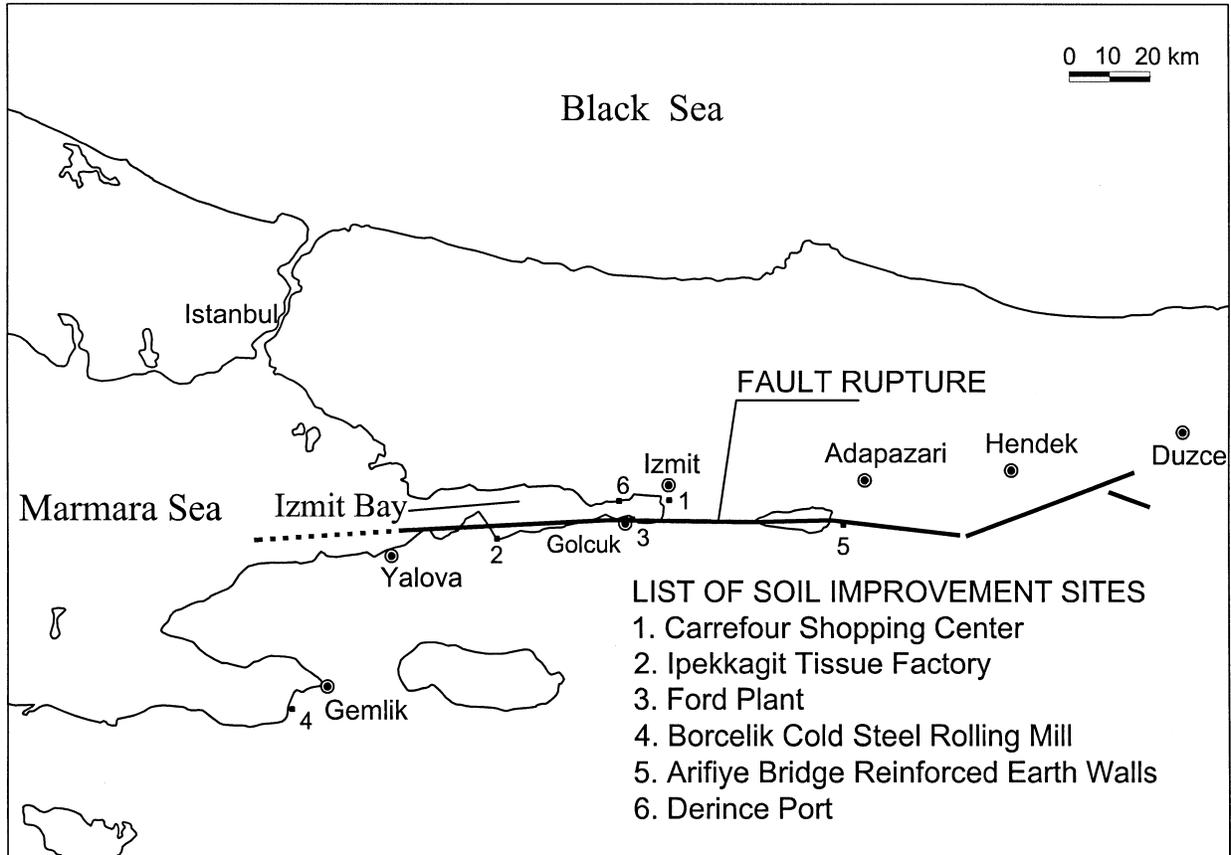


Figure 1. Affected area and soil improvement sites.

This paper summarizes the results of the field reconnaissance and preliminary analyses of four sites where ground modification was used to improve the soils. Detailed case study including numerical analysis is just beginning and comprehensive results are not yet available; however, the research objectives and plans for collaboration with other researchers are presented.

The sites included mostly industrial and commercial developments. As shown in Figure 1, the sites are located along Izmit Bay, ranging from 0 to 35 km from the fault rupture. With the exception of Derince Port, geotechnical data for each of these sites have been collected. Arrangements were made to obtain geotechnical and soil improvement data for the Derince Port, but these data were not available at the time of this writing. Detailed analyses of the reinforced earth wall at Arifiye are in progress and preliminary findings will be presented in a companion paper.

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

## **Carrefour Shopping Center**

The Carrefour Shopping Center is located in the city of Izmit, approximately 8 km from the earthquake epicenter, and 5 km from the closest observed surficial fault rupture. Peak ground accelerations in this area were in the range of 0.2g. The soil profile consists of recent marine sediments with alternating strata of medium clay and loose sand.

The soils were improved to increase bearing support for shallow foundations and reduce liquefaction potential of the sand layers. Buildings at the complex were in the early phases of construction when the earthquake occurred. Data from geotechnical investigations and instrumentation installed for construction settlement monitoring made possible the detailed assessment of the seismic performance of the site and the effectiveness of soil improvement. Of particular importance, this site provided the rare opportunity to measure the settlement of a liquefiable sand layer subjected to strong ground shaking. The observations also allowed qualitative comparisons between the seismic performances of improved sections of the site relative to adjacent unimproved areas.

### ***General Site Information and Soil Conditions***

The Carrefour site is situated within a Quaternary-aged marine sedimentary plain with level ground conditions. As shown in Figure 2, the site covers an area of about 55,000 m<sup>2</sup> and will house two main facilities. A large supermarket is located at the eastern end of the site, and a two-story parking garage is located at the opposite end. Both structures are supported on shallow foundations.

Geotechnical field investigations included 17 Standard Penetration Tests (SPTs), 108 Cone Penetration Tests (CPTs), and 4 test pits (Zetas 1998b, Martin and Olgun, 2001). Irregularly placed sandy-gravelly fill extends from the ground surface to a depth of about 2.5 m. A medium clay stratum that extends from a depth of 2.5 m to 6.0 m underlies the fill. Below the clay, a stratum of fine-to-silty sand is encountered in a loose-to-medium dense condition. The thickness of this sand layer ranges from 2 m to 4 m across the site. Penetration data indicate that this layer is liquefiable under strong ground shaking. Below the sand, a second stratum of medium silty clay is encountered that extends from 10 m to a depth of more than 30 m where the exploration was terminated. The ground water table is found within 2 m of the ground surface throughout the site.

### ***Foundation System and Soil Improvement***

The structures at the shopping center are founded on shallow footings and mats. The primary foundation design issues were large anticipated settlements and bearing problems in the clay, along with liquefaction of the loose sand layer. Surcharge fills were used to improve the soft clays, and jet-grout columns were used to provide increased bearing support in the clays and prevent liquefaction of the loose sands.

The spacing, treatment depth, and construction details for the jet-grout columns varied from location to location due to differing soil conditions and foundation configurations. Jet-grout column spacings and diameters were selected mainly on the basis of footing spacing, footing loads, floor slab loads, and judgment. No rigorous analyses were performed to modify the spacings for liquefaction performance criteria. Rather, it was tacitly assumed that the jet-grout columns installed for foundation support, along with a secondary rectangular grid installed between the primary columns, would be sufficient to significantly reduce potential liquefaction-

related damages (see spacing details in following sections). With the exception of the Lot C area and most of Parking Structure area, all ground improvement had been completed and the foundations recently constructed when the earthquake struck.

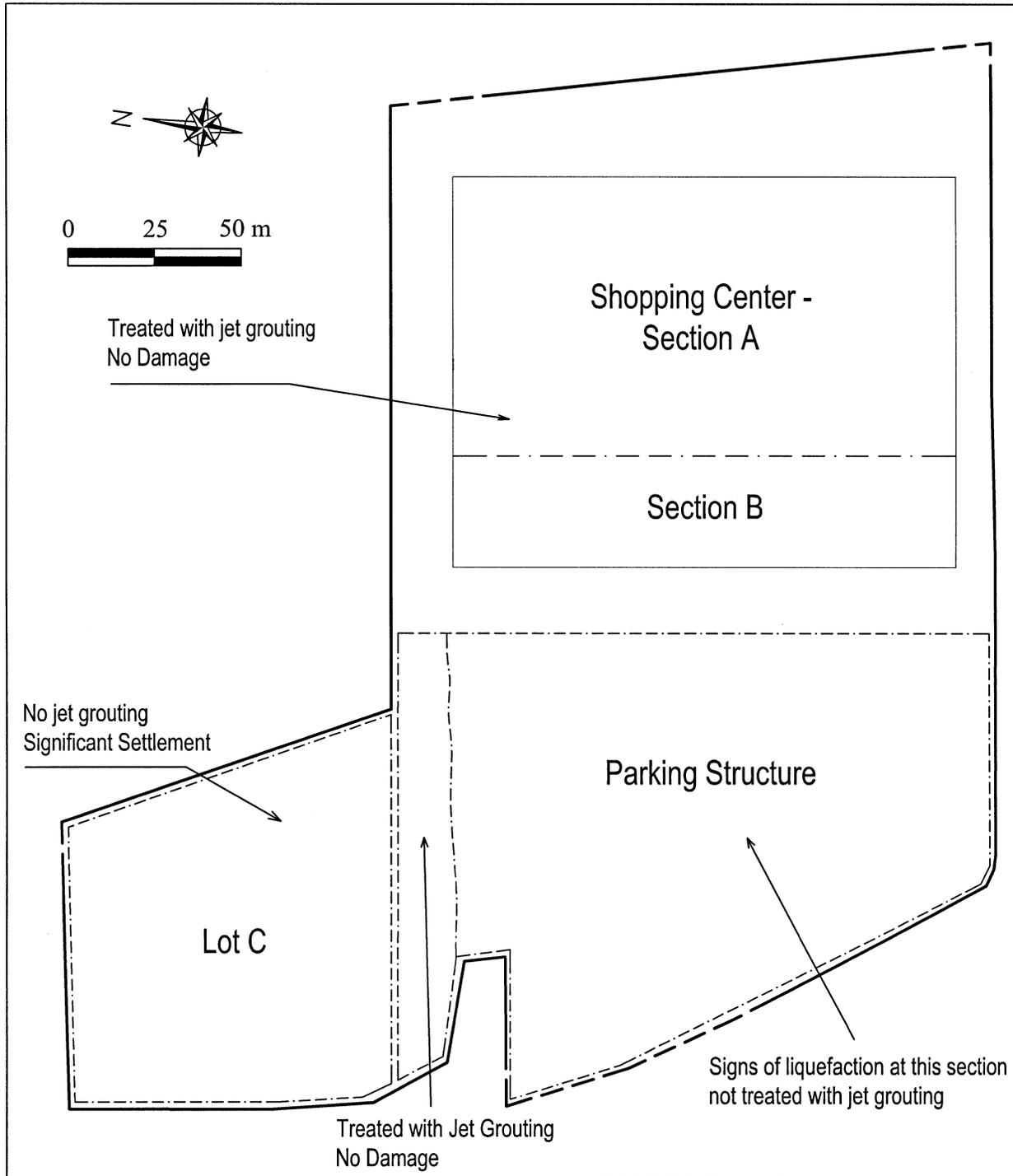


Figure 2. Carrefour Shopping Center – site plan

**Supermarket Building Area.** The supermarket is a one-story structure covering an area of approximately 15,600 m<sup>2</sup>. Section A of the building is founded on isolated spread footings, while Section B is supported by a mat foundation. The soils in both sections were preloaded with a 3.5 m-high fill that was present at the site for a substantial period of time before construction.

In addition to preloading, jet-grout columns were constructed to improve bearing support and reduce settlements of the clay, and to increase liquefaction resistance of the underlying sand layer. A primary and secondary grid of columns was installed in a rectangular pattern 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 in between the primary columns to further increase the liquefaction resistance of the 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 m to 9.0 m.

In addition to the primary and secondary grids, 0.6 m-diameter columns were also installed at each spread footing location in Section A of the supermarket building. Groups of two and four jet-grouted columns were installed beneath the exterior and interior footings, respectively. Section B, which will rest on a mat foundation, was blanket-treated with 9.0 m long, 0.6 m-diameter columns installed at a 1.5 m center-to-center spacing.

**Parking Structure Area.** The soils in the parking structure area were proposed to be improved in the much the same manner as those for the supermarket area. The parking area has an area of about 14,000 m<sup>2</sup>. The structure is founded on shallow isolated footings, with a slab poured between the footings to tie the foundation system together. The site was surcharged with a 3.3 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. The surcharge was removed after consolidation was complete and was not in place at the time of the main shock.

Jet-grouted columns were proposed for the parking area in primary and secondary grids to provide blanket treatment for the area. The primary grid of 0.6 m-diameter grouted columns is in a rectangular pattern with a 2.5 m-center-to-center spacing. The columns extend from the ground surface to a depth of 9 m into the lower medium clay stratum. The secondary grid included shorter columns that penetrate only the liquefiable sand layer, which is about 4 m thick in this area of the site. In addition to the primary and secondary grids, jet-grout columns were installed directly under each footing for the parking structure. At the time of the earthquake, less than 10% of the Parking Structure area had been treated with jet-grout columns.

**Lot C Area.** Lot C, is located adjacent to the Parking Structure and encompasses an area of 4,160 m<sup>2</sup>. No structures were initially planned for this section, but the soils were proposed to be improved in anticipation of future development. Similar to the other treated areas, Lot C was surcharged with a 3.3 m-high fill and 20 m-long wick drains were installed. Settlement columns were installed to monitor settlements at several depths within the soil profile. The surcharge fill was in place during the earthquake, and settlements of the clay strata were being monitored on a regular basis. Jet-grout columns had not yet been installed in this area.

#### ***Field Performance During Earthquake Loading***

The steel framework for the supermarket building were in place at the time of the earthquake. Visual field inspections following the earthquake indicated that no structural damage occurred in

the supermarket building and no noticeable settlements or ground damages were observed anywhere at the site except in the untreated portion of the Parking Structure area and Lot C.

Site personnel reported that the untreated portion of the Parking Structure area was inundated with about 7 to 10 cm of water that temporarily ponded on the ground surface the morning following the earthquake as shown in Figure 3. It may be remembered that wick drains were installed in this area, and a surcharge fill was removed prior to the earthquake. Field inspections determined that the water originated from the underlying soil deposit via drainage through the wicks. It is fortuitous that settlement-measuring devices were in place at Lot C during the earthquake. By comparing pre- and post-earthquake readings from within the soil profile, the earthquake-induced settlement of the sand layer could be closely estimated. It was found that 8.0 cm of settlement occurred in the 2 m-thick loose silty-sand layer, presumably due to pore pressure build-up and subsequent reconsolidation via drainage through the wicks. It is also possible that the wick drains provided partial drainage during the earthquake, although the silty sand is not expected to be free-draining. To our knowledge, this type of earthquake-induced settlement measurement is unprecedented and provides an opportunity to better understand saturated sand behavior under strong ground shaking. Also, the measured settlement of 8.0 cm in the loose sand layer compares well with the 7 to 10 cm of water ponding on the surface, as the amount of extravasated water should be reflective of the volumetric strain induced in the sand layer. It is important to note that no surficial ground disruptions, such as sand boils, occurred at this location. The wick drains are thought to have prevented liquefaction and/or provided efficient drainage of the sand during reconsolidation, although significant settlements still occurred.



Figure 3. Ponding of water at portions of the parking structure area that were not yet treated with jet grout columns, Lot C under the preload fill is visible at the back – photograph taken the morning after the earthquake from the site border looking north

Field reconnaissance also revealed that structures in an apartment complex located across the street from the shopping center commonly experienced settlements of 5 to 10 cm. Based on soil boring and CPTs in this general area, it is probable that the loose sand stratum underlying the shopping center also underlies the apartments.

It is instructive to note that Lot C and parts of the Parking Structure area were the only areas at the site that had not been improved with jet-grouted columns. All other areas within the boundaries of the site had been improved with both primary and secondary grids of jet-grouted columns to reduce liquefaction susceptibility. Based on the differences in performance between the unimproved and improved areas (including structures across the street founded on unimproved soils), the jet-grouted columns installed at the site appear to have been effective in reducing liquefaction susceptibility and liquefaction-related settlements of the sand layer. A detailed study is being conducted to more thoroughly investigate the effectiveness of the improvement and the behavior of the instrumented sand layer.

### **Ipekkagit Tissue Factory**

The Ipekkagit Tissue Factory is located along the southern waterfront of Izmit Bay, The site lies approximately 4 km from the fault rupture. Maximum acceleration at the site reached about 0.3g during the main shock as estimated from nearby recordings and distance to the zone of energy release. General layout of the site is shown in Figure 4. The soils at the site consist of alternating strata of clay and sand that were improved for the support of shallow foundations. Geotechnical data were available from recent construction projects at the plant (Zetas 1997, 1998a) Following the earthquake, visual inspections revealed minor structural damage in an older building that was founded on unimproved ground. No structural or ground damage occurred in areas where the soils were improved.

Subsoil investigations performed for recent construction projects were made available to the present study. Geotechnical data were obtained for the new extension to the Paper Machine Building No.3 (PM3), the Reel Storage Building, and two large water tanks. Construction of the Reel Storage Building and the water tanks was completed about one year before the Kocaeli Earthquake, and the PM3 Building was under construction at the time of the event. The soil investigations for these projects included ten Standard Penetration Tests (SPTs) and 25 Cone Penetration Tests (CPTs). The penetration tests revealed alternating strata of medium-to-stiff clay and medium-to-dense sand to a depth of more than 20 m where the exploration was terminated.

At PM3 building location, a medium-to-stiff clay layer of medium plasticity extends from the ground surface to a depth of 3 m. Below the clay is a stratum of clean sand of medium density that extends from 3.0 m to a depth of 6.0 m. From 6.0 m to 9.0 m, a medium-dense silty sand layer is encountered. Below 9 m, a stratum of stiff-to-hard clay is found that extends to the bottom of the boring at a depth of 32.0 m. In some borings for this area, a medium dense sand layer was also found between depths of 24 m and 27 m. The water table was found at a depth of 1.5 to 2 m. The PM3 soil profile can be considered representative of the entire plant site; however, specific soil data for the other structures were also available.

The soil profile at the water storage tanks varied slightly from that at the PM3 location. A clay stratum layer of medium stiffness and plasticity extends from the ground surface to a depth of approximately 4 m. Below the clay between the depths of 4 m and 10 m, a sand layer of

medium density is found. Below the sand, a stiff-to-hard clay layer is encountered that extends from 10 m to the bottom of the boring at a depth of 20 m.

Subsoil conditions at the location of the Reel Storage Building were similar to those at the PM3 area. At the top of the soil profile, a medium-to-stiff clay stratum of medium plasticity is found. The depth to the bottom of this stratum is variable throughout the building area, ranging from 1.8 m to 4.5 m. From a depth of 4.5 m to 6.5 m, a gravelly sand layer is found in a medium-dense condition. A medium-dense silty sand layer is found between the depths 6.5 m and 8.5 m. Below 8.5 m, a stratum of stiff-to-hard clay extends to a depth of 18.0 m where a very dense sand layer is encountered.

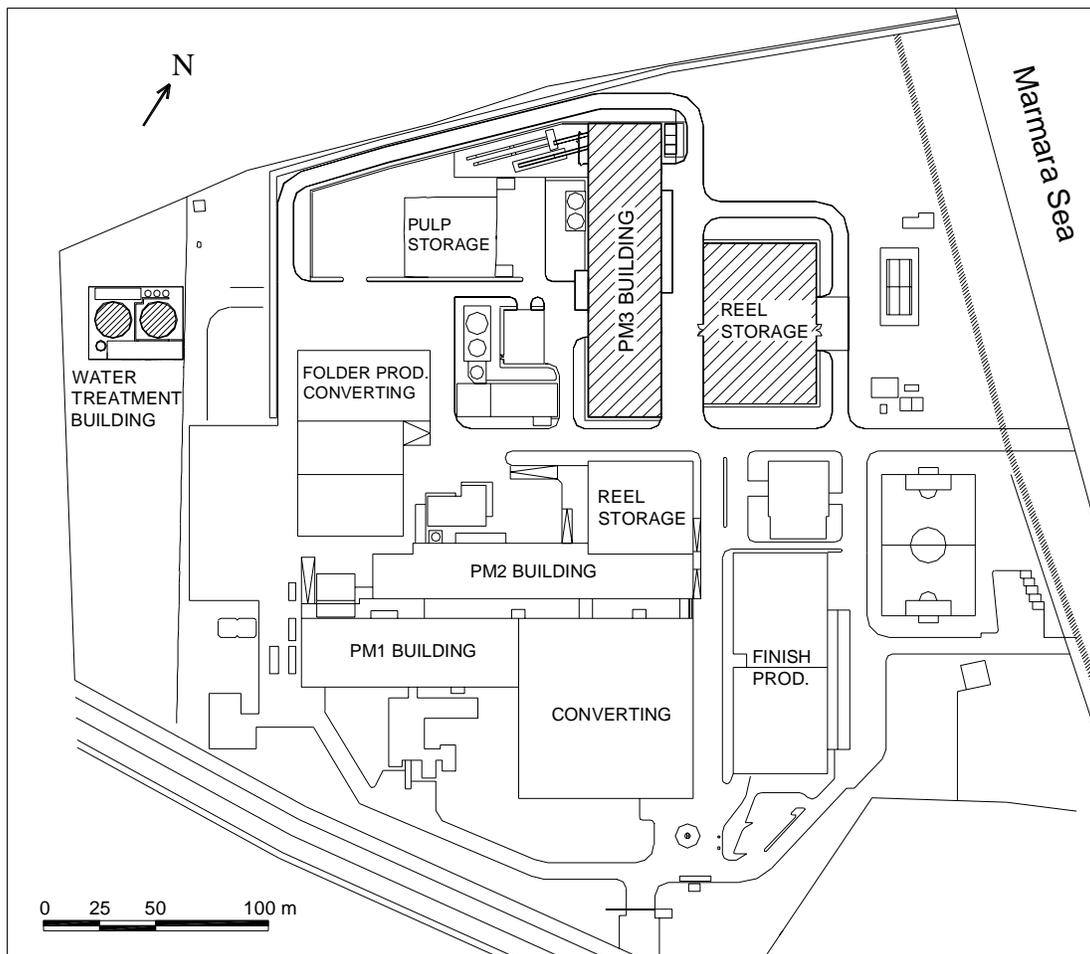


Figure 4. Ipekkagit tissue factory – site plan

#### ***Foundation System and Soil Improvement***

Jet-grout columns were constructed to improve ground conditions and as foundation support members for recently constructed facilities at the site. In addition to soil treatment, the top 2 m of clay was excavated and replaced with a compacted sand-and-gravel fill for improved bearing support beneath slabs.

The PM3 Building, being constructed at the time of the earthquake, is supported by a reinforced-concrete mat foundation. To improve the soils in this area, jet-grout columns 12 m long and 0.6 m in diameter were installed beneath the mat in a rectangular grid pattern. Center-to-center column spacing ranged from 1.2 to 2.4 m. Two additional rows of grout columns were constructed around the perimeter of the building to provide additional foundation support. These columns were 8.0 m long and spaced at 1.4 m center-to-center. Grout column spacings and diameters were selected mainly on the basis of foundation loads, as no detailed analyses were made to modify the columns for liquefaction prevention; however, it was assumed that the columns would significantly reduce liquefaction-related problems.

Following jet-grouting, CPTs were performed in the areas between the columns. Comparison of CPT soundings before and after jet-grout columns indicate that no significant increase in penetration resistance was achieved, as would be expected, as the jet-grouting process installs reinforcing columns but does not densify the in-situ soil.

The water tanks are supported by a mat foundation. Jet-grout columns 10.5 m long and 0.6 m in diameter were constructed beneath the mat. The columns were installed in a rectangular grid pattern, with a 2.0 m center-to-center spacing. The Reel Storage Building is supported by 4.0 m-wide strip footings. Jet-grout columns 8.0 m in length and 0.6 m in diameter were constructed beneath the footings. The column spacing ranged from 1.2 m to 2.4 m.

### ***Observed Field Performance During Earthquake Loading***

Following the earthquake, a visual inspection of the plant revealed no major earthquake-related damages. All facilities remained operational during and after the earthquake. Only minor structural damage occurred in one of the older buildings (PM2 Building) where a heavy concrete facing element fell off the exterior of the building, and an interior reinforced-concrete column developed cracks about 1 cm-wide. No structural damage occurred anywhere else at the plant. The foundation soils for the PM2 building were not improved. Thus only structural damage occurred at an area where the foundation soils were not improved.

No signs of liquefaction or ground movements were found anywhere at the plant. Surprisingly, there were also no liquefaction-related features found along the northern waterfront or at neighboring sites, all of which contained untreated liquefiable soils. The lack of liquefaction-related ground evidence in these areas was unexplained (0.03g peak acceleration), and meant that effectiveness of the soil treatment for liquefaction mitigation could not be determined based on behavioral distinctions between treated and untreated ground.

### **Ford Plant**

A Ford automobile factory, located near the town of Golcuk, was under construction at the time of the earthquake. The site was located essentially at the zone of energy release, as the surficial fault rupture passed along the western edge of the site. The soil profile consists mainly of liquefiable sands and soft clays. The site was improved using jet-grout and stone columns to support shallow foundations and mitigate liquefaction. Significant structural damage occurred to one building, and minor liquefaction was observed at the site. Also, the site underwent large-scale ground subsidence due primarily to fault-related tectonic deformation. The geotechnical data for this site are taken from Saglamer (1998) and Osmanoglu (1999).

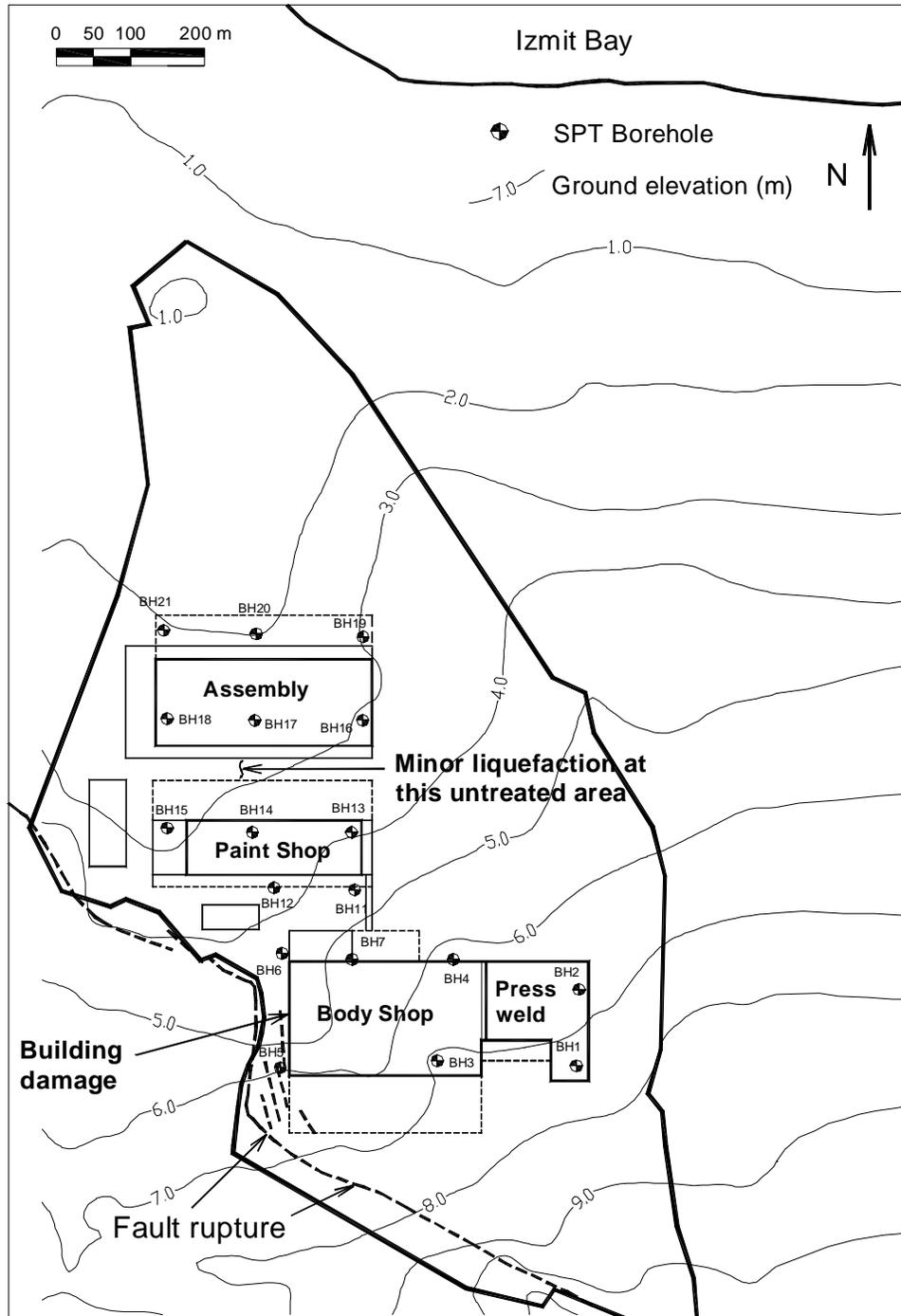


Figure 5. Ford plant – site plan

***General Site Information and Soil Conditions***

The plant encompasses a total area of about 1.5 km<sup>2</sup> (150 hectares) and is located within a deposit of Quaternary-age marine and alluvial sediments. A site plan with ground elevation contours prior to the earthquake is provided in Figure 5. The site is bordered by Izmit Bay to the

north. Prior to the earthquake, the ground surface sloped downward towards the Bay, from an elevation of +10.0 m at the southern end of the site to about +2.0 m near the bay. The surficial manifestation of the fault rupture from the earthquake ran along the western edge of the site.

Subsoil investigations at the site consisted of 27 Standard Penetration Tests (SPTs) to an average depth of 20 m. The investigations indicated varying soil conditions with alternating layers of clays and sands. The most prevalent soil profile is one that includes a layer of soft clay and/or loose sand from near the ground surface to a depth of about 5 m. SPT blow counts for the sandy levels and clayey levels range between 2-5 blows/ft and 2-7 blows/ft respectively. Below these upper strata, a medium-to-dense gravelly sand stratum is found with interbedded lenses of stiff clay. The ground water table is found within 1 m of the ground surface.

***Foundation System and Soil Improvement***

Major plant facilities include the Press Shop, Body Shop, Paint Shop, and the Assembly Shop. The structural loads for each of these facilities are large, and are typically supported by isolated spread footings resting on drilled shafts or jet-grout columns. The presence of the compressible soils in the upper 5 m of the profile made necessary the improvement of the soils for adequate bearing support and reduces liquefaction susceptibility. A combination of stone columns and jet-grouting was used for soil treatment across the site, as summarized in Table 1. Approximately 200,000 m of jet-grout columns were installed, along with 90,000 m of 0.8 m-diameter stone columns.

Table 1. Main structures - foundation systems and soil improvement

<b>Structure</b>	<b>Dimensions (m x m)</b>	<b>Column Spacing (m x m)</b>	<b>Soil Improvement</b>	<b>Foundation System</b>
Body shop	140 x 280	6 x 20 16 x 20	Jet-grout & stone columns	Single footings on improved ground
Paint shop	85 x 125	10 x 10	Jet-grout columns	Drilled shafts
Assembly shop	120 x 296	6 x 20 16 x 20	Jet-grout columns	Single footings on improved ground
Press shop	150 x 165	8 x 28	Jet-grout columns	Drilled shafts

**Body Shop.** The Body Shop is supported on isolated spread footings, with a slab-on-grade poured between the footings to tie the foundations together. Jet-grout columns and stone columns were constructed for soil improvement and foundation support. Groups of four jet-grout columns, at a 2.6-m center-to-center spacing were installed under each footing. The columns are 0.8 m in diameter and 10 m in length. Stone columns of 0.8 m diameter and 10 m length were constructed at a 2 m center-to-center spacing to improve the soil beneath the base slab.

**Paint Shop.** The Paint Shop is supported on isolated spread footings, with a slab-on-grade poured between the footings to tie the foundations together. Group of four drilled shafts at 2.4 m spacing were installed beneath each footing. The drilled shafts under each footing have lengths

of 15 to 18 m, and diameters of 0.65 m to 0.8 m. Jet-grout columns 0.8 m in diameter and 10 m long were installed at 3.3 m center-to-center spacings to improve the soil under the slabs.

**Assembly Shop.** The Assembly Shop is supported on isolated spread footings, with a slab-on-grade poured between the footings to tie the foundations together. A group of four jet-grouted columns were installed beneath each footing. These columns were 0.8 m in diameter, 10 m long, and installed at a spacing of 2.7 m center-to-center. Jet-grout columns of the same size and length were also installed on a grid pattern with a 2.7 m center-to-center spacing to provide blanket improvement of the soils beneath the base slabs.

**Press Shop.** The foundation system for the Press Shop consists of isolated spread footings and reinforced-concrete mats poured in excavated channels (sunken, rectangular pits typically 8 m x 20 m in plan and 8 m deep) that will house heavy equipment. Groups of four drilled shafts with 2.4 m center-to-center spacing were constructed beneath each spread footing. The drilled shafts are 18.0 m long with diameters of 0.8 m. Six rectangular reinforced-concrete channels with widths varying between 8.0 m and 10.0 m were constructed within the building for the foundations of machinery. The base of each channel is 8.0 m below the ground surface. Diaphragm walls were used to support the excavations during construction, and the base of the excavations were sealed against water inflow by jet-grouting. Drilled shafts of 0.8 m diameter at 2.4 m center-to-center spacings were installed to support the weight of the channels. The shafts are 12 m long and the tops of the piles are 8.5 m below the ground surface. Between the piles, jet-grouted columns of 0.8 m diameter with 2.4 m center-to-center spacings were installed. The columns are 5 m long, and the bottoms of the columns are 13.5 m below the ground surface.

#### ***Observed Field Performance During Earthquake Loading***

Following the earthquake, a visual inspection of the plant revealed significant earthquake-related damages. The most prominent observation was that the entire site underwent a global subsidence of about 2.5 m due to movements associated with the surficial fault rupture passing along the western plant boundary. The Body Shop, located closest to the fault rupture, underwent differential foundation movements of about 1 m, resulting in severe structural damage to the building. No signs of obvious liquefaction were found at the building and it is presumed that most of the damage was fault-related; however, it is possible that liquefaction-related phenomena may have played a role. The Body Shop is being demolished and re-built.

Small sand-boils and limited settlements, indicative of minor liquefaction, were observed in an open area between the Assembly Building and Paint Shop where the soils were not treated. Lateral spreading was observed along the waterfront in the general vicinity of the plant, but no spreading or any other signs of liquefaction were observed anywhere at the site. The liquefaction appears to have been confined to areas where the soils were unimproved. This difference in behavior between untreated and treated ground suggests that the soil treatment was effective in reducing liquefaction-related damages.

Another interesting observation was that the surficial fault rupture appeared to change course where it intersected the plant site to follow the western property boundary. It is not clear whether this localized behavior was related to a pre-existing ground weakness such as an old fault scarp, or possibly, differences between the heavily-treated ground at the plant site and the untreated ground of the surrounding area.

## Gemlik Borcelik Steel Mill

The Borcelik Steel Rolling Mill is located near the town of Gemlik, about 50 km from the earthquake epicenter and 35 km from the zone of energy release of the earthquake. Accelerometer recordings in Gemlik indicate that peak ground accelerations on rock were 0.10g. The soil profile is highly variable, consisting of a mixture of sensitive soft clays and liquefiable sands. Stone columns were installed to provide blanket treatment of the site. Ground shaking levels at the plant were relatively low during the main shock, and no structural or ground damages were observed.)

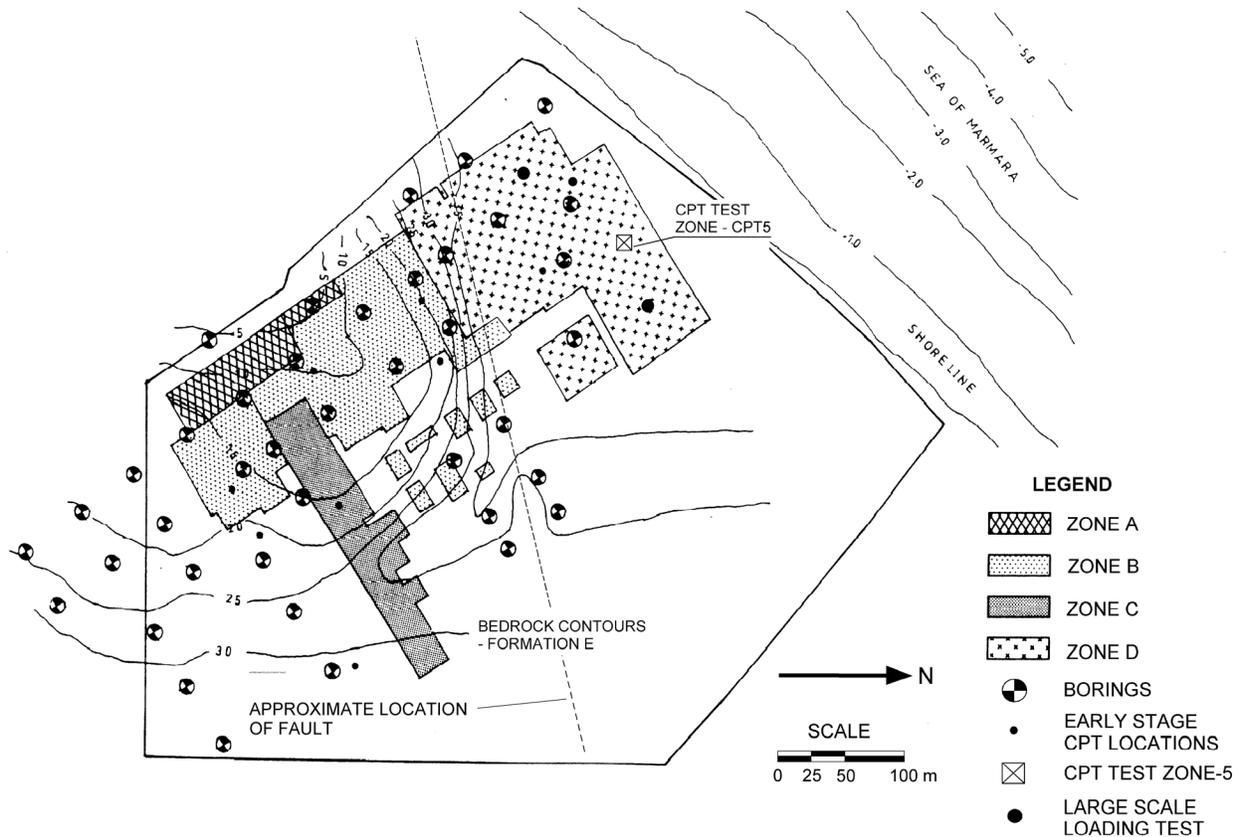


Figure 6. Borcelik steel mill – site plan

### *General Site Information and Soil Conditions*

The plant site covers an area of 0.5 km<sup>2</sup> (50 hectares), with a nearly flat surface topography. Geologic maps indicate that the site is situated within a deposit of Quaternary marine sediments. The maps also show that the Southern Marmara branch of the North Anatolian Fault passes through the site, as further evidenced by the many abrupt changes in bedrock elevations at the site. The general layout of the site is shown in Figure 6.

Subsoil investigations at the plant site included 90 Cone Penetration Tests (CPTs). The soil profile was found to be highly variable across the site, consisting of soft sensitive clays, loose sands, and outcropping rock. A single representative soil profile is difficult to develop for

the site, although the major portion of the site included soft sensitive clays and loose, liquefiable sands (Zetas 1991). The ground water table is found within 1.5 m of the ground surface. Because of the variable soil conditions, the site is grouped into four distinct zones and the conditions within each of these zones are described below:

Zone A: Conditions in this area consist of primarily of highly-weathered bedrock that is found either at very shallow depths or exposed.

Zone B: The profile in this area consists of sandy and silty overconsolidated clay from the ground surface to a depth of 4.0 m. (The thickness of this layer increases to as much as 7.0 m at the northern end of the site in Zone D). Below the clay stratum, is a loose-to-medium sand stratum, containing occasional gravel lenses. Lenses of soft sensitive clays are found interbedded in the sand at some locations. CPT resistances in the layer indicated the sand to be liquefiable under strong ground shaking

Zone C: Soils in this area are mainly stiff to very stiff overconsolidated clays with gravel lenses. Bedrock is found at a depth of about 20 m.

Zone D: The stratigraphy is quite similar to that of Zone C, consisting mainly of stiff overconsolidated clay, but the soil profile is much thicker as bedrock is found deeper than in any other location across the site. In some CPTs that extended to a depth of 60 m, the bedrock was not encountered.

### ***Foundation System and Soil Improvement***

Foundations at the site are required to support large structural loads from heavy machinery and steel stockpile storage areas. The main factory building and heavy equipment supports are founded on 0.8 m- and 1.2 m-diameter bored piles. The stock storage areas, with up to 200 kN/m<sup>2</sup> bearing pressure, are supported on reinforced-concrete mats overlying improved ground. Stone columns were used to increase bearing capacity beneath the mats and provide blanket treatment of the liquefiable sands across the entire site. In areas where the bearing stratum was relatively shallow, the stone columns were extended full depth to the bearing stratum. In areas where the bearing stratum was deep, stone columns were terminated at a 12 m depth. The stone columns were constructed by driving a closed-end pipe to depth, and then backfilling the pipe with stone as it was vibrated and slowly pulled out. The stone columns were installed in a triangular grid with a 1.5 m center-to-center spacing.

During the early phases of site work, CPTs were performed to determine optimum stone column spacing and to assess the extent of soil improvement. Several test sections with stone columns at various spacings were constructed. The optimum stone column spacing was selected from the comparison of CPT before- and after-treatment CPT measurements at these trial sections.

CPTs were also used during stone column construction to assess the degree of soil improvement for comparison with final design requirements. The area of stone column treatment was divided into sections, each having 200 to 400 stone columns. Six CPTs were performed in each section, with two performed before treatment, and four after treatment. It was found that the CPT tip resistances increased by about 75% in the sandy layers as a result of stone column construction. A typical pair of before and after CPT soundings is shown in Figure 7 (Durgunoglu et al. 1995).

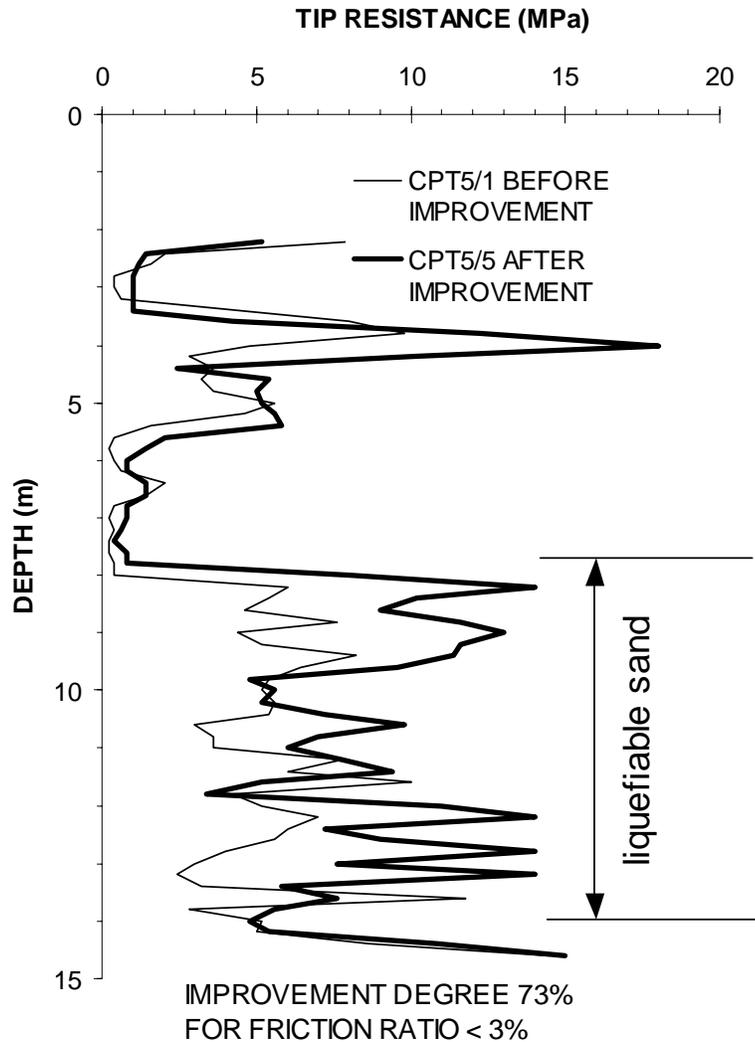


Figure 7. Typical CPT soundings before and after treatment

***Observed Field Performance During Earthquake Loading***

Following the Kocaeli Earthquake a visual inspection of the plant revealed no earthquake-related structural or ground damages. The ground shaking levels at the plant were relatively low, estimated in the range of 0.1g. The plant remained operational during and immediately following the earthquake. No cracks or signs of settlements were observed in the concrete floor slabs, and no ground cracks were observed anywhere across the site. Importantly, neighboring areas along the waterfront, including the port area of the plant that contained untreated liquefiable soils suffered no damages or obvious signs of ground movements. Further, other nearby industrial facilities in the Gemlik area reported either no or only minor damage. The relative lack of ground damage in the surrounding region, along with the relatively low ground shaking levels at the site, made difficult a more rigorous assessment of the effectiveness of the ground improvement.

## Conclusions And Directions For Future Research

Following the August 1999 Kocaeli Earthquake in northwestern Turkey, field reconnaissance and preliminary analyses were conducted at a number of sites in the affected region. Primary emphasis was upon sites where ground modification was used to improve soils. Findings at four soil improvement sites are presented here. The sites range from 0 to 35 km from the zone of energy release and encompassed a wide range of soil conditions that required a variety of ground improvement techniques to mitigate earthquake related damages. Importantly, the performance comparison of sites of unimproved ground located adjacent to treated sites could be used in some cases to help gauge the effectiveness of soil treatment upon seismic mitigation. As of this writing, the necessary geotechnical have been collected and detailed analyses are just beginning; however, preliminary findings can be provided:

- 1) There were a number of sites within the affected region of the earthquake that contained liquefiable sands and medium to soft clays that were improved for seismic mitigation purposes. The soils at these improved sites performed better compared to nearby/adjacent unimproved soils.
- 2) Jet-grout columns and stone columns were generally effective in mitigating seismic damages, especially liquefaction-related damages; it is believed that the stone columns and jet-grout columns decreased shear strains (and thus pore pressure development) in the soils. Also, the jet-grout columns appear to have greatly reduced post-earthquake reconsolidation settlements in the sands.
- 3) The presence of wick drains appear to have prevented liquefaction and surficial ground disruption due to a loose, liquefiable silty-sand layer, although settlements were still significant.
- 4) The Carrefour Shopping Center site is a particularly instructive case history because of the unprecedented direct measurement of the earthquake-induced settlement of a liquefiable sand layer.
- 5) Detailed analyses are needed to better evaluate the effectiveness of the soil improvement at each site. This project would benefit from collaborative research with other investigators working on similar studies.

With these preliminary findings in hand, the research plan for this work involves detailed studies of the field sites to better understand the effectiveness of soil improvement in mitigating earthquake-related damages. A primary tool will be parametric numerical analyses using computer codes such as FLAC (Itasca Consulting, 2000). Preliminary analyses of the sites using this code have already begun. The study will rely on field performance data from recent earthquakes in Turkey, Taiwan, Seattle, Washington, and other locations. If possible, data from model tests and centrifuge studies will be incorporated to better calibrate the soil model and extend the performance database. The primary research objective is to develop guidelines that

can be used to design soil improvement schemes to mitigate earthquake-related damages. For instance, it is important to understand the number, size, and stiffness of jet-grout columns required to prevent liquefaction and/or greatly reduce settlements. It would be particularly beneficial to develop a collaborative relationship with other researchers working on soil improvement projects, especially those involved with model tests and/or centrifuge studies. Data from these studies, along with results from this project, would be mutually complementary.

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