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FIELD EVIDENCE AND LABORATORY TESTING OF THE CYCLIC VULNERABILITY OF FINE-GRAINED SOILS DURING THE 1999 KOCAELI EARTHQUAKE

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ABSTRACT

Significant earthquake-induced settlements occurred in saturated fine-grained soils at the Carrefour Shopping Center in Turkey during the 1999 Kocaeli Earthquake (M=7.4). Most of the settlement was due to the undrained cyclic failure of silt/clay (ML/CL) and high-plasticity clay (CH) strata within the subsoil profile. Each suffered about 1% vertical strain. Extensive laboratory testing on undisturbed samples from these silty and clayey strata has been performed to investigate this behavior. The laboratory testing included monotonic and cyclic simple shear tests, triaxial tests and conventional 1-D consolidation tests. Considerable pore pressure increases have been measured during cyclic simple shear test which was later followed by significant reconsolidation settlement. It was found that significant pore pressures begin developing in these soils at cyclic stresses at about 50% of their monotonic shear strength. This transition in behavior with high pore pressure development and subsequent post-cyclic volume changes corresponds to about 0.5% cyclic shear strains. The study demonstrates the limitations of generalized liquefaction screening methods, and dispels the common misconception that high plasticity soils cannot generate high pore pressures and fail under cyclic loading. Test results indicate that the soils at the site can generate significant pore pressures when shaken at levels expected to have occurred during the Kocaeli Earthquake. The findings from this study are inline with the limited number of studies on this topic. Fine-grained soils, if shaken hard enough, can suffer strength loss and reconsolidation settlements. The challenge remains to better understand such phenomenon and incorporate this into engineering practice. This paper presents the observed ground failure at the site, site characterization studies and following laboratory testing program.

INTRODUCTION

The Kocaeli Earthquake (M=7.4) struck northwestern Turkey on August 17, 1999 and caused significant damage in urban areas located along Izmit Bay. Following the event, the authors investigated the area to document the performance of improved soil sites (Martin et al. 2004). The Carrefour Shopping Center was of interest because the site was under construction at the time of the earthquake, and contained both improved and unimproved soil sections that could be compared in terms of seismic performance. The shopping complex is located along Izmit Bay as shown in Figure 1, approximately 3 km from the ruptured fault.

The soil profile consists of recent marine sediments with alternating strata of soft-to-medium clay, silt-clay mixtures, and loose sands. The water table is within 2 m of the surface. Peak ground acceleration at a nearby rock site was 0.23g during the earthquake. Construction was ongoing when the earthquake struck, and the soil beneath the main building had been improved using jet-grout columns. Most of the site, as well all of the surrounding properties, remained on unimproved soil. Following the earthquake, the authors inspected the complex and neighboring sites to compare the performance of treated and untreated areas.

Fortuitously, settlement extensometers had been installed in an unimproved area (Lot C in Figure 2) a few weeks prior to the earthquake for monitoring settlements beneath a 3.3-m surcharge fill. Approximately 12 cm of earthquake-induced settlement was measured. Most of the settlement was associated with undrained cyclic failure of silt/clay (ML/CL) and high-plasticity clay (CH) strata that suffered an average of about 1% vertical strain. Nearby, five- and six-story apartment buildings on untreated ground exhibited similar earthquake-induced failures, with typical settlements of 10-12 cm.

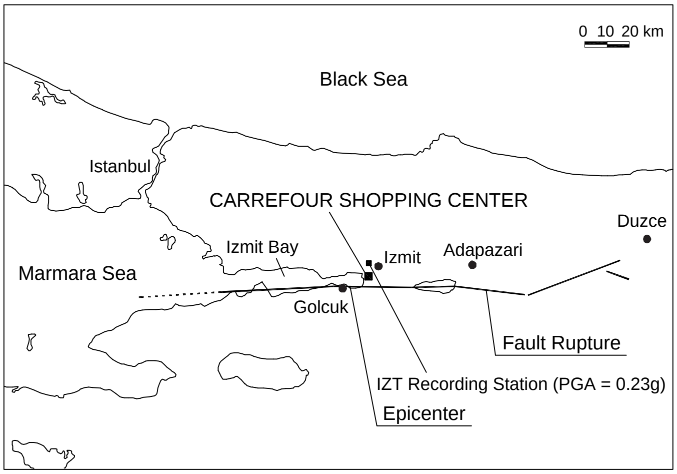

Fig.1. *Map of affected area of 1999 Kocaeli Earthquake (M7.4) and location of Carrefour*

Because the CH and ML/CL soils were plastic and did not meet the commonly-used Chinese criteria due to high clay content, they were classified as "non-liquefiable," and the designers did not anticipate them being a source of significant earthquake-induced deformation. As the measurements indicate however, these soils were vulnerable to significant cyclic deformation. Of particular importance, the findings imply that generalized liquefaction screening guidelines are not reliable predictors of seismic vulnerability and, especially, cyclic deformation potential. Further, the authors believe this case demonstrates the importance of defining what soil behavior is being referred to when the term liquefiable or non-liquefiable is used. An earlier study (Martin et al. 2004) focused on the effectiveness of the soil improvement used at Carrefour site. This paper focuses on the behavior of the unimproved fine-grained soils beneath the fill and nearby buildings. The case demonstrates what we feel is a widespread underappreciated and misunderstood seismic vulnerability of these soils.

SITE LAYOUT AND SUBSOIL CONDITIONS

Carrefour Shopping Center is 55,000 m^2 in plan area and situated along Izmit Bay, about 3 km from the ruptured fault of the 1999 Kocaeli Earthquake. The main shopping center was being built when the earthquake occurred, and Lot C was being surcharged will a 3.3-m fill and wick drains. The site is underlain by alternating strata of irregular fill, silt-clay (ML/CL), poorly graded sand / silty sand mixture (SP/SM), and high plasticity clay (CH); the water table is within 2 m of the ground surface.

Representative soil conditions are shown in Figure 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 within the upper 25 m. SPT $N_{1,60}$ blowcounts are less than 10 blows/ft. in most strata. The shear wave velocity profile is constant to a depth of 25 m, averaging about 140 m/s. The SP/SM stratum was of primary concern during foundation and soil improvement design. This layer ranges from 1.5 to 4 m in thickness across the site and on average contains 15% non-plastic fines.

Index properties of the soils at the site are summarized in Table 1. The ML/CL strata contain an average of more than 50% clay-sized particles (< 5μm) [although 2μm is usually considered the clay-size boundary, 5μm is used for the Chinese criteria as suggested by Seed and Idriss (1982)]. For this strata, the liquid limit is, LL = 33, the natural water

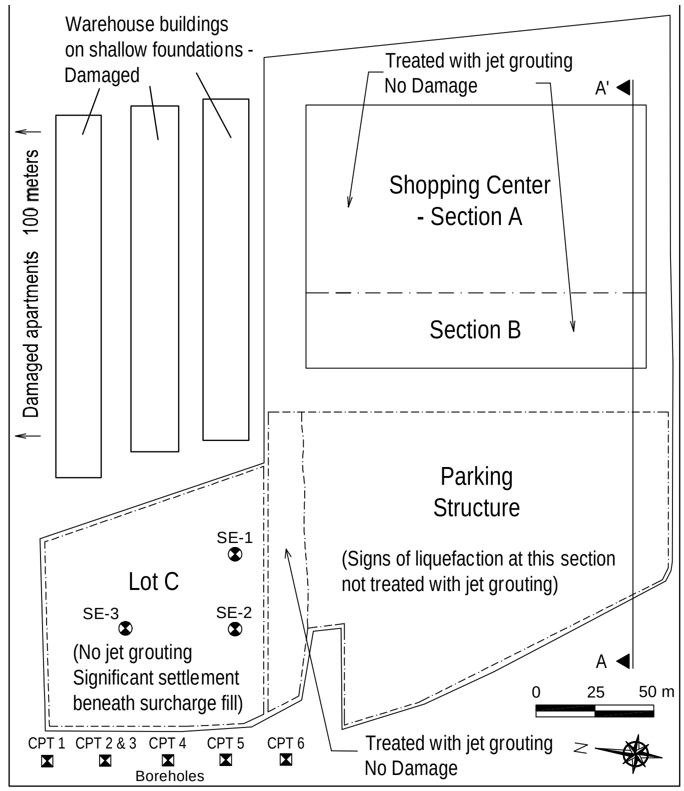

Fig. 2. Carrefour site plan

content, w = 32%, and the plasticity index, PI = 10. In assessing the liquefaction susceptibility of these soils during design, the engineers used the Chinese Criteria which classify soils as "suspect" if the percent clay (5μm) < 15%, LL < 35, and w > 0.9 x LL.

The ML/CL classifies as non-liquefiable because only two of the three criteria are met: the water content is approximately equal to LL, and LL < 35 (LL=33), but the soil contains nearly 50% clay-sized particles, far more than the 15% specified. The soil behavior type index, I_c, from the CPTs averaged 3.0 for these strata. Current consensus guidelines (Youd et al. 2001) are unclear in the characterization of such materials, suggesting that such soils with I_c > 2.6 are too clay-rich to liquefy.

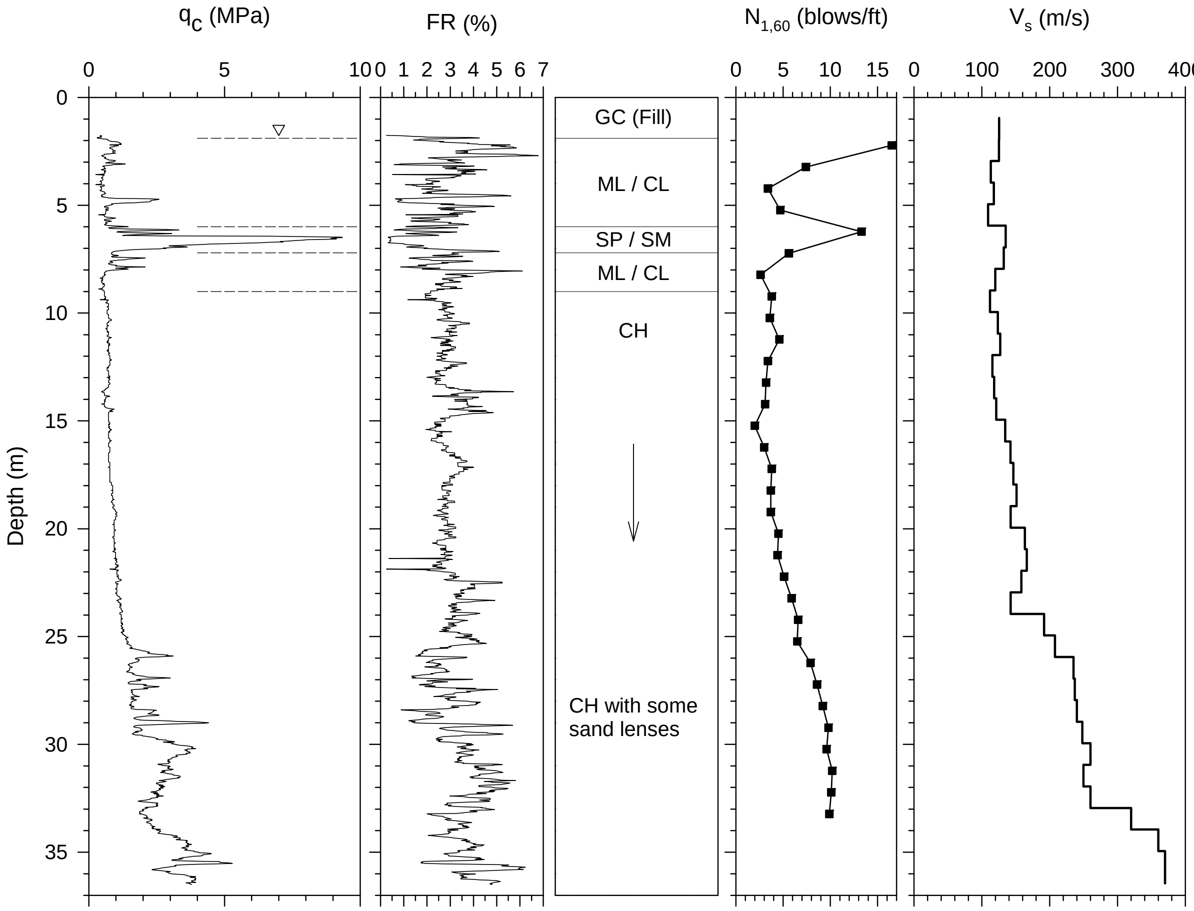

Fig. 3. Soil profile at Carrefour site

Table 1. Average grain size and index test data for soil strata at Carrefour site

Depth of Stratum (m)	USCS	LL (%)	PI (%)	w (%)	> #4 sieve (%)	< #200 sieve (%)	< 5 µm (%)	< 2 µm (%)	I_c Value from CPT*
0 to 2	Fill (GC)	-	-	-	-	-	-	-	-
2 to 6.5	ML/CL	33	10	32	0	88	47	38	3.0
6.5 to 9	SM w/ SP, SC lenses	NP	NP	24	6	30	16	14	2.2
9 to 10	ML/CL	35	11	33	0	95	55	42	2.9
10 to 35	CH w/ SM, ML lenses	66	37	55	0	100	74	61	3.3

* I_c = soil behavior type index (Lunne et al. 1997)

Nevertheless, significant cyclically-induced settlements were associated with these strata. More recent studies by Bray et al. (2004) suggest such silt-clay mixtures may be susceptible to seismic failure.

Finally, the CH stratum at Carrefour site contains an average of 74% clay with LL = 66, PL = 29, PI = 37, and w = 55%. The CH soils are classified as "non-liquefiable" by the methods (i.e. Chinese Criteria) at the time of design and were

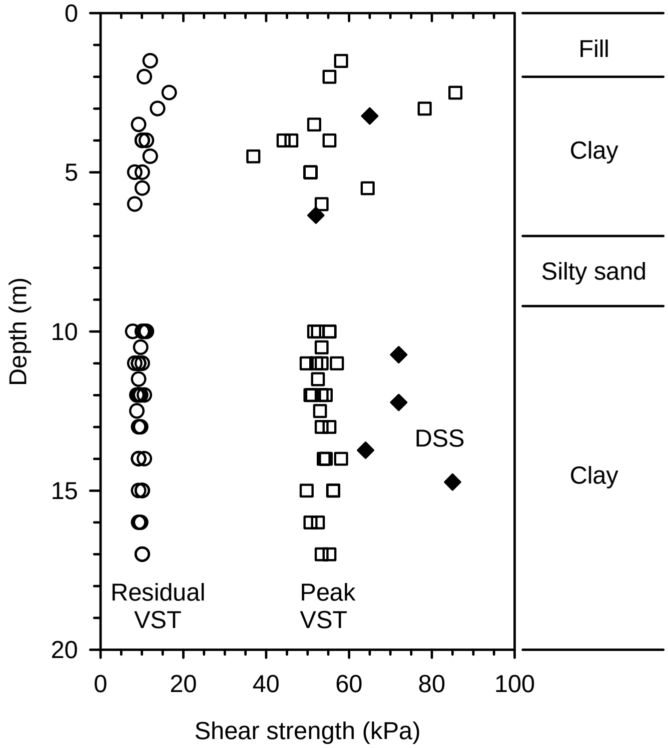

Fig.4.Shear strength measurements from vane shear testing and simple shear testing

considered by site engineers to be immune from significant pore pressure increases and deformation during shaking. However, current methods (Bray et al. 2004) also consider these levels "non-liquefiable" due to their high plasticity. But, similar to the ML/CL strata, significant settlements were attributed to the CH soils.

A liquefaction analysis was performed and an average factor of safety against liquefaction of about 0.7 is estimated for the SP/SM and ML/CL soils in the upper 10 m using the simplified approach developed by Youd et al. (2001) and Bray et al. (2004). The CH soils are considered "non-liquefiable" by these methods. Using the more recent approach recommended by Boulanger and Idriss (2006) for "clay-like" soils, and accounting for K_α beneath loaded areas such as the surcharge fill, the estimated factor of safety is about 0.85 for the ML/CL and CH soils in the upper 15 meters of the profile. Although there is uncertainty in the estimated strengths and cyclic resistances, it is clear that there was a significant potential for seismic failure and deformation, as observed in parts of the site. Therefore additional investigations were necessary to better gauge the strength and pore pressure generation characteristics of these soils. These investigations summarized below provide information to better understand the cyclic vulnerability of the silty-clayey soils at the site.

FIELD AND LABORATORY TEST RESULTS

Additional field investigations and laboratory testing have been recently performed for comprehensive characterization of the soils at Carrefour site. The work consisted of in-situ vane shear testing, monotonic and dynamic strength testing with triaxial and simple shear devices. A total of 40 field vane shear tests were performed within the clayey levels along the profile and the results are shown in Figure 4. It is also seen from the comparison of the peak and residual strength measurements that the soils at the site have a sensitivity ratio ($S_{u\text{-residual}}/S_{u\text{-peak}}$) of about 5. Undrained shear strength values measured with monotonic simple shear tests run on high-quality undisturbed soil samples are in close agreement with the vane shear test results. In-situ and laboratory shear strength measurements indicate that the ML/CL and CH has average strength ratios S_u/σ_{vo}' of 0.6-0.7 and 0.5, respectively. These rather large strength ratios are indicative of slight overconsolidation of the soils at the site. 1-D consolidation tests found OCRs to be about 2-3 in the ML/CL and 1.5 in the CH, respectively.

Laboratory testing program was designed to answer questions, such as: the stress history, the peak and residual undrained shear strength of the soils and how do they respond under different levels of cyclic loading. Of particular interest was to see if the soils were susceptible to significant pore-pressure build up and softening as implied by the measured settlements. The laboratory testing included monotonic and cyclic simple shear tests, triaxial tests and conventional 1-D consolidation tests. Cyclic simple shear tests are conducted at confining pressures that correspond to the sample depths and at CSR (τ/σ_{vo}') values between 0.1-0.4. The estimated CSR for the soil profile during the Kocaeli Earthquake was around ~0.3.

The laboratory testing program is recently completed. A typical stress path of shear stress and vertical effective stress for the cyclic simple shear testing of the CH soil is shown in Figure 5. During this test the specimen was subjected to a CSR of 0.35 and loaded for 25 stress cycles. The monotonic shear loading of the same soil is also shown for comparison. Undrained shear strength of 65 kPa is measured from the monotonic simple shear test. This value is very close to the in-situ vane strength measurements shown earlier. For comparison, the CSR of 0.35 corresponds to an applied shear stress to undrained shear strength ratio (τ_{EQ}/S_u) of 0.67. It can be seen from the stress path of the cyclic test that the soil exhibits a contractive tendency and generates a pore pressure ratio (r_u) of 75% at the end of 25 cycles of loading. Collectively, however, the DSS tests show that both soils (ML/CL and CH) exhibit excess pore pressure ratios less than 30% for CSRs (0.2-0.25) at 15 cycles of loading. A dramatic degradation in cyclic strength is seen at a CSR of 0.35 and higher.

A compilation of the measured excess pore pressures in relation to the maximum shear strain that developed during simple shear testing is shown in Figure 6. As seen, pore

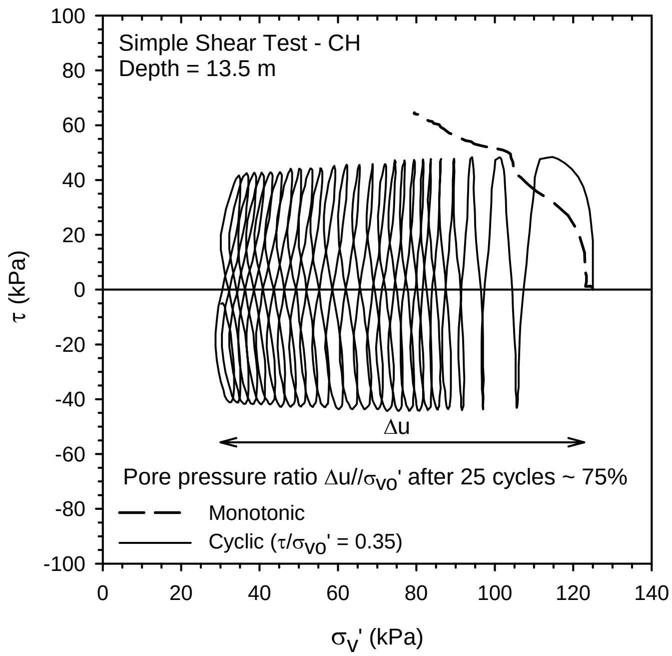

Fig. 5. Cyclic simple shear test results of high plasticity clay sample

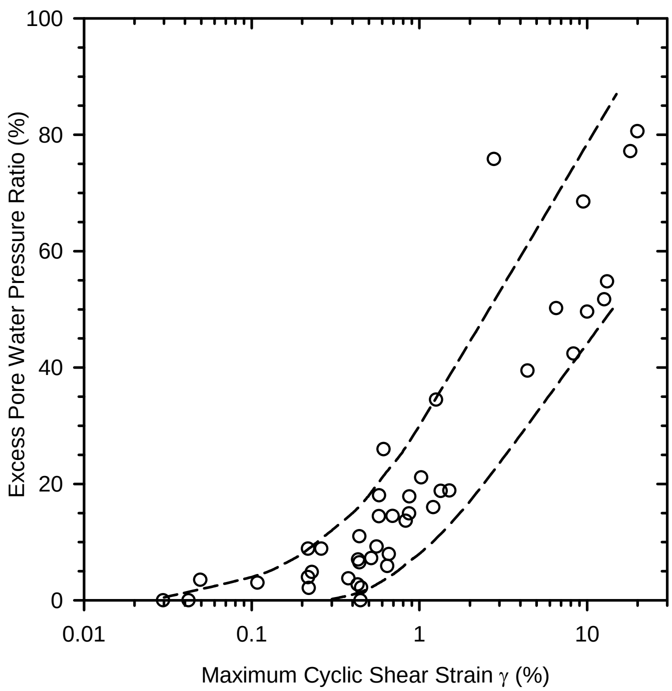

Fig. 6. Measured excess pore pressures

pressure generation below 0.5% shear strain is limited and significant pore pressures start developing after this threshold level. In addition, volumetric strains measured following cyclic loading are shown in Figure 7. Similarly, post-cyclic volumetric strains are limited below this threshold strain. At higher levels of loading, the amount of volumetric strain in relation to the maximum shear strain is consistent with earlier results reported by Castro (1987) from tests conducted on silty and clayey soils.

CONCLUSIONS

The Carrefour Shopping Center is located along Izmit Bay in northwestern Turkey. The site is underlain by saturated soft clays, silts, and liquefiable sands, and was subjected to strong ground shaking during the 1999 M7.4 Kocaeli Earthquake. The site was under construction at the time, and extensometers were in place that allowed earthquake-induced settlements and strains beneath a 3.3-m fill to be measured. Such measurements are unprecedented and provide unique insights. The principal points are:

1. Cyclic failure in the form of significant cyclic deformation (1% vertical strain) was demonstrated in saturated fine-grained soils, including silt/clay mixtures (ML/CL) and high plasticity clays (CH), and this vulnerability was not predicted by engineers using current liquefaction guidelines.

2. The "non-liquefiable" classification of plastic fine-grained soils has led to the widespread misconception that such soils are somehow immune from pore pressure development and cyclic failure. This has, in turn, led to a widespread underappreciated seismic vulnerability of these soils. This case also points out the importance of specifying the

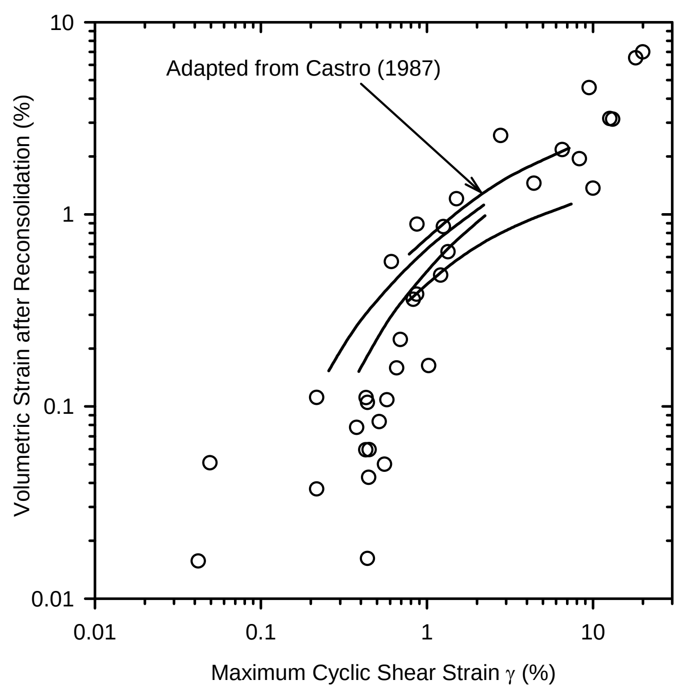

Fig. 7. Post shaking volumetric strains

corresponding soil behavior when the term liquefiable or non-liquefiable is used.

3. Generalized screening guidelines, such as the Chinese criteria or I_c values from CPTs, have severe limitations for identifying seismic failure potential, and should not be used. The recent method proposed by Boulanger and Idriss (2004) for clay-like soils appears to provide reasonable predictions of the observed behavior at Carrefour.

4. The Carrefour site is still being investigated, and the full lessons have yet to be learned. As of this writing, a comprehensive laboratory testing program on undisturbed specimens, along with field vane shear testing have been performed. Preliminary evaluation of the test results indicate that the soils at the site exhibit pore pressure generation potential at loading levels expected to have occurred at the site during the 1999 Kocaeli Earthquake.

5. In evidence of these tests it is possible that the soils at the site lost strength and softened during the earthquake. We believe that the observed settlements at the site during the earthquake are closely related to this phenomenon.

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