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ABSTRACT

The Kocaeli Earthquake (M=7.4) struck Turkey on August 17, 1999 and caused significant damage along Izmit Bay. Following the earthquake, the authors investigated the field performance at improved soil sites. Of particular interest was the Carrefour Shopping Center that was under construction during the earthquake. The reclaimed site is underlain by strata of saturated soft clays, silts, and liquefiable loose sands. Small-diameter jet-grout columns had been installed at close spacings to reduce settlements and prevent liquefaction-related damage beneath footings and mats. Nonlinear dynamic three-dimensional finite element analyses were conducted to model the reinforced ground at Carrefour. The results show that the primary benefit of the columns was different than first suspected. That is, we initially thought the higher composite stiffness of the reinforced ground led to reduced seismic shear stresses and shear strains in the soil mass. However, the numerical results show that the reinforced ground did not behave as a composite mass during shaking due to strain incompatibility between the soil and stiff columns. The results indicate that the columns did not significantly reduce seismic shear stresses and strains (and thus pore pressures) in the soil mass. The effectiveness of the jet-grouting at Carrefour was more related to the vertical support the columns provided that prevented seismically-induced settlements. The implication is that commonly-used design methods and assumptions may lead to overestimates of the effectiveness of ground reinforcement for mitigating seismic damage.

INTRODUCTION

Ground improvement using stiff columnar reinforcement, such as stone columns, jet grout and soil-mix columns is commonly used for mitigation of seismic ground damage in soils susceptible to significant seismic-induced deformation. A number of benefits are gained, such as in-situ densification of loose granular soils where stone columns are installed, and increased bearing support where jet-grout or soil–mix columns are constructed in fine-grained soils that cannot be effectively densified. In current engineering practice shear stress reduction in the reinforced soil mass is considered a key factor in reducing the seismic vulnerability of soils improved with stiff columns. The shear stress reduction mechanism of stiff columns is based on the presumption that the stiff columns attract more of the seismically-induced shear stress than the surrounding softer soil mass. The idea that the column carries larger shear stress, in proportion to the stiffness ratio, is implicitly based on the assumption that both the soil and the stiff columns deform compatibly in shear, namely undergoing the same shear deformation. This assumption is further utilized in calculating the reduction of seismically induced shear stresses on the soil (Baez and Martin 1994). In this paper we present the results from the study where numerical analyses were conducted to study the effectiveness of jet-grout columns at Carrefour Shopping Center during the 1999 Kocaeli Turkey Earthquake.

The Kocaeli Earthquake (M=7.4) struck northwestern Turkey on August 17, 1999 and caused significant damage in urban areas located along Izmit Bay (Martin et al. 2001). The Carrefour Shopping Center was of particular interest because the site was under construction at the time of the earthquake, and contained both improved and unimproved soil sections that could be compared in terms of seismic performance. The facility is approximately 3 km from the ruptured fault. The peak ground acceleration on rock near the site was measured about 0.2g (Olgun 2003).

The soil profile at Carrefour consists of young marine sediments with alternating strata of clays, silt-clay mixtures, and loose sands. Jet-grout columns of 9-m length and 0.6 m in diameter were installed at 4-m spacings to provide bearing support and mitigate potential liquefaction-related damage beneath shallow foundations. Jet grouting had been completed for the main building and the structure was about 60% complete when the earthquake struck. Grouting was just beginning in a neighboring area, and thus most of the site remained on unimproved ground. A post-earthquake field reconnaissance found stark differences between the improved and unimproved ground. The treated area suffered no measurable settlements or other forms of ground damage, whereas the unimproved sections, along with untreated building sites nearby, commonly suffered earthquake-induced settlements of up to 10-12 cm.

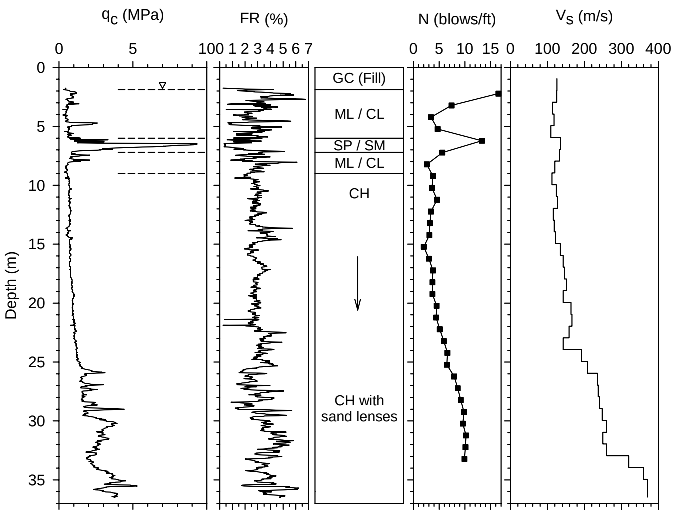

Figure 1. Soil profile at the site

Three dimensional dynamic nonlinear finite element analyses have been performed to investigate the seismic performance of jet-grout treatment. Although, it was clear that the ground treatment was effective, our analyses suggest that the seismic behavior of the reinforced ground and the primary reason for its effectiveness was different than first thought. The reinforced ground likely did not behave as a composite soil mass, as commonly assumed by some widely-used design methods (i.e. Baez and Martin 1994). This means the dynamic shear stresses and strains in the soil were not significantly reduced by the reinforcement. Rather, we suspect the effectiveness was primarily related to the vertical support of the columns that reduced earthquake-induced settlements. The study has implications for the use and design of reinforced ground for seismic mitigation.

SITE LAYOUT AND SOIL CONDITIONS

The Carrefour Shopping Center is situated in a Quaternary marine setting of low ground elevation and minimal local relief. The site is underlain by soft alluvial sediments consisting of alternating strata of soft clays, silt-clay mixtures, and silty sands. The water table is within 2 m of the surface. Representative geotechnical data are presented in Figure 1. As shown, the stratigraphy is variable, consisting of alternating strata of silt-clay mixtures, silty sands, and soft-to-medium clays. The Cone Penetration Test (CPT) tip resistances are low, and with the exception of the silty sand stratum (SP/SM), the values average about 1 MPa throughout the upper 25 m of the profile. Standard Penetration Test (SPT) $N_{1,60}$ blowcounts average 5 blows/ft. in most strata. Shear wave velocities measured by seismic CPTs are 110-140 m/sec throughout the upper 25 m.

Of concern to the designers was the potential liquefaction of the loose-to-medium SP/SM stratum found at an average depth of 6 m. This stratum varies from 2 to 4 m in thickness across the site and contains and average of 30% non-plastic fines. And although not understood at the time, the ML/CL

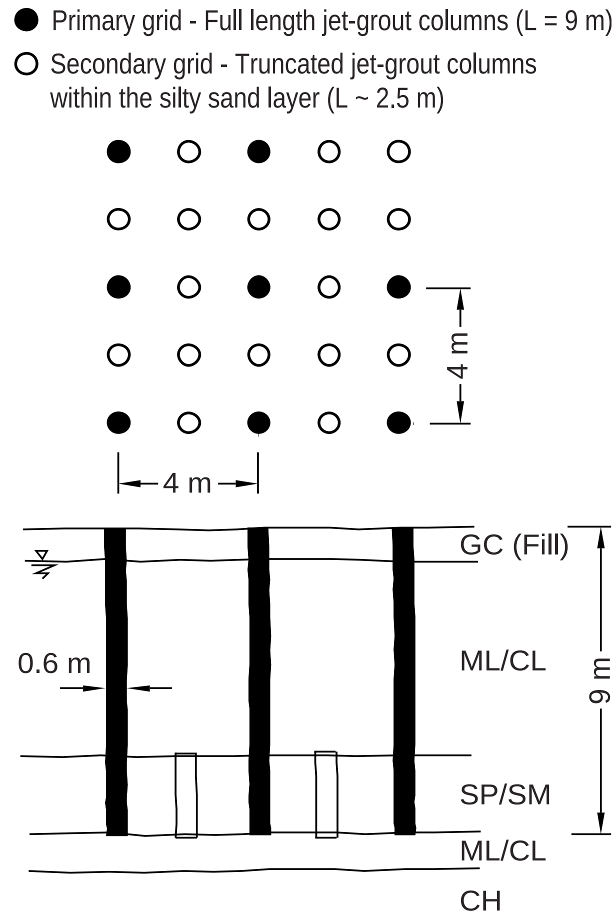

Figure 2.J et-grout column layout

and CH strata were also vulnerable to significant earthquake-induced deformations beneath loaded areas, as measured by site engineers after the earthquake. The ML/CL has a PI = 10 and LL = 34, whereas the CH has a PI = 37 and LL = 66.

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

As shown in Figure 2, primary and secondary grids of jet-grout columns were installed to provide blanket treatment. The primary columns were 0.6 m in diameter with a center-to-center spacing of 4 m, and extended from the ground surface to a depth of 9.0 m. A secondary grid of 2.5 m-long columns was installed between the primary columns. These truncated columns, which penetrated only the SP/SM stratum, were installed with the tacit assumption that the higher jet-grout replacement in this layer would reduce liquefaction potential. The average area replacement ratio beneath the building was about 2% for the ML/CL stratum, and 7% for the SP/SM stratum. Average 7- and 28-day unconfined compressive strengths from core samples were 2.0 MPa (280 psi) and 4.8

MPa (690 psi), respectively (Emrem 2000). These values are typical of single-fluid jet-grout columns in fine-grained soils. A post-earthquake field inspection showed dramatic differences in the performance of the improved section relative to the untreated areas. No settlements or signs of ground damage were found beneath the supermarket building, and construction resumed following the event. In stark contrast, significant settlements occurred in unimproved sections at the site and neighboring properties, including some level-ground areas as well as most areas that were loaded with fills or buildings, including relatively light structures.

DYNAMIC NUMERICAL MODELING

Although the columns were demonstrated to be effective at mitigating ground damage, the specific mechanisms were unclear. It was initially assumed that the primary benefit was the higher composite shear stiffness of the reinforced ground that reduced seismic shear stresses and strains, as suggested by Baez and Martin (1994) in their method proposed for stone columns. They propose the use of stress reduction factor (K_G) based on area replacement ratio and relative shear stiffness of the soil and stiff columns (G_{column}/G_{soil}). In their approach, the composite behavior of the reinforced soil mass, and thus strain compatibility between the soil and stiff columns, is implicitly assumed. To investigate this and other potential mechanisms, advanced dynamic nonlinear finite element modeling of the reinforced ground at Carrefour was performed using Dynaflow (Prevost 1981).

The reinforced ground, treated with 4m x 4m grids of primary (9-m long) and secondary (2.5-m long) 60 cm-diameter columns was dynamically modeled in three dimensions. Plan view of the model is shown in Figure 3. The unit cell is developed to contain the 9-m long jet-grout columns at the center. The truncated columns within the silty sand layer are located at the sides of the model. The finite element mesh contained approximately 22,000 elements and is shown in Figure 4. As shown, the model of the soil profile extended to a depth of 15 m. Detailed soil testing data were not available at the time to calibrate the constitutive models for fully-coupled pore pressure generation behavior. Therefore, the modeling wase performed with total stress analyses, where pore pressure generation was not considered. We believe that this is an adequate approach for the purpose of investigating the shear load transfer mechanism between the columns and the soil. Constitutive soil parameters were based on laboratory and

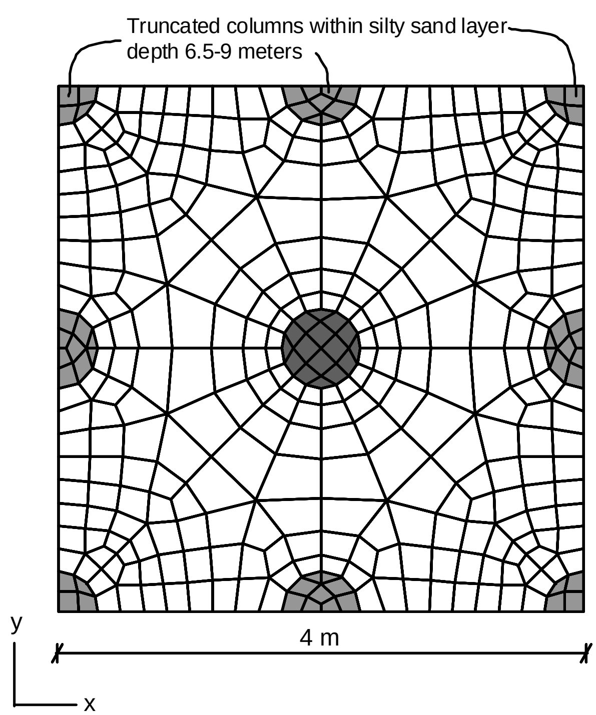

Figure 3. Plan view of the jet-grout column layout in the finite element model

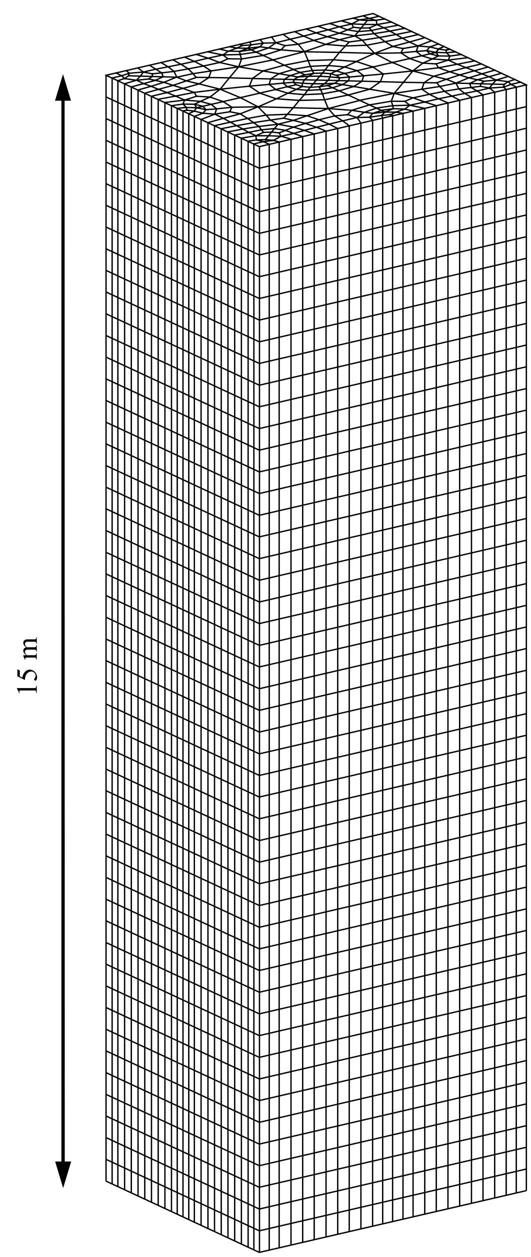

Figure 4. Finite element mesh of the 3-D model

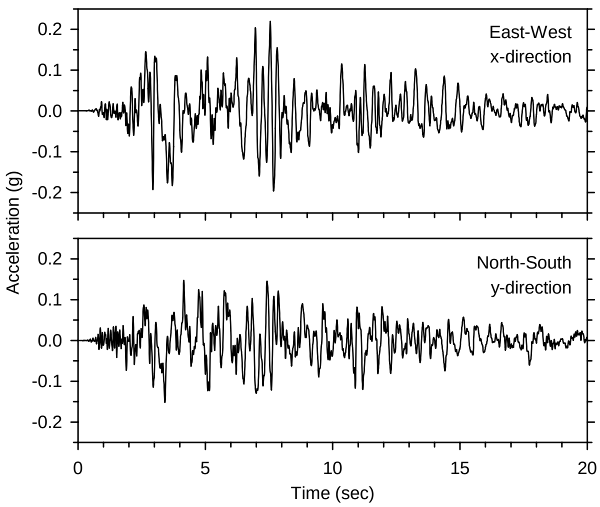

Figure 5. Components of base motion used in the analysis

field tests performed by the authors (Olgun 2003), and the soils were modeled to be fully nonlinear during shaking using the multi-yield surface elasto-plastic soil model developed by Prevost (1981). The jet-grout columns were modeled with strengths and stiffnesses consistent with those measured during post-treatment field quality control tests mentioned above. To provide a benchmark for judging the effectiveness of the jet-grout columns, a series of runs was also performed for the case where the columns were removed from the model such that the soil was unimproved.

In terms of boundary conditions along the sides, the three-dimensional model was assumed to be surrounded by an infinitely repeating sequence of identical 4m x 4m reinforced soil sections. This was achieved by assigning the opposite nodes on each face of the model to be equivalent. By assigning nodal equivalency to node couples at the same elevation along opposite faces, they share the same set of equations of motion, and therefore undergo the same motion in each direction. This equivalency imposes symmetry along each vertical face of the model and therefore a repeating sequence is defined. For each run, the models were shaken in two horizontal directions simultaneously using the horizontal components of the ground motions recorded in Izmit (IZT station) during the 1999 Kocaeli Earthquake as shown in Figure 5. The IZT recording site is located approximately 2 km from Carrefour. Of primary interest in the analyses was the shear load transfer mechanism between the jet-grout columns and the soil and thus evaluating the effectiveness of the columns in reducing shear stresses and strains in the reinforced soil mass. This analysis did not consider pore pressure generation and post-earthquake behavior

ANALYSIS RESULTS

The stresses and strains were computed along the two horizontal directions (x and y), as per the three-dimensional analysis (τ_{zx}, τ_{zy} and γ_{zx}, γ_{zy}). The absolute maximum value that occurred during the analysis was selected at the nodes.

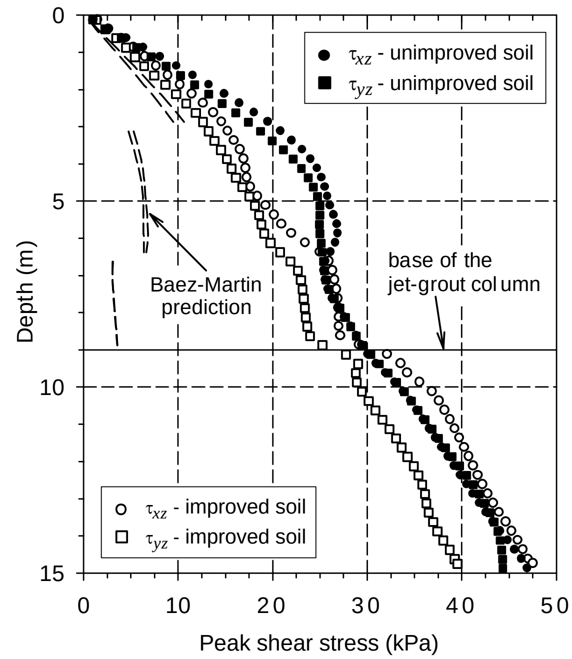

Figure 6. Calculated peak shear stresses in the improved and unimproved soil profiles

Furthermore, these peak values at the nodes were averaged within each elevation. Figure 6 shows the calculated peak seismic shear stresses developed within improved soil mass in comparison to the shear stresses in the unimproved profile. Also provided are the shear stresses predicted by the Baez-Martin approach based on the unimproved shear stresses and the corresponding shear stress reduction factors within the jet-grout improved profile. It can be seen that the jet-grout improvement at the top 9 meters have only slightly reduced the shear stresses. Had the Baez-Martin approach worked, the stresses would be significantly reduced to levels shown in the figure. These results are indicative that the Baez-Martin approach to shear stress reduction does not capture the seismic behavior of columnar reinforced ground.

Looking further in terms of the implications for design practice, a comparison is made between the shear stress reduction predicted by the commonly-used Baez and Martin (1994) method for stone columns and the stress reduction from our analyses. This comparison is shown in Figure 7. As seen, the Baez-Martin method predicts the average shear stress reduction in the improved soil would be as high as 90%. But as shown, the actual stress reduction predicted is nowhere near this amount, only in the 20%-30% range – many times less than that predicted by Baez and Martin (1994).

In an attempt to clarify such discrepancy between the Baez-Martin method and the computed shear stress reduction, the relative magnitudes of shear strain between the jet-grout columns and the soil in the reinforced zone were investigated. As mentioned above, the Baez-Martin method is based on the assumption that the soil and the stiff column at each elevation undergo the same magnitude shear deformations. As a result

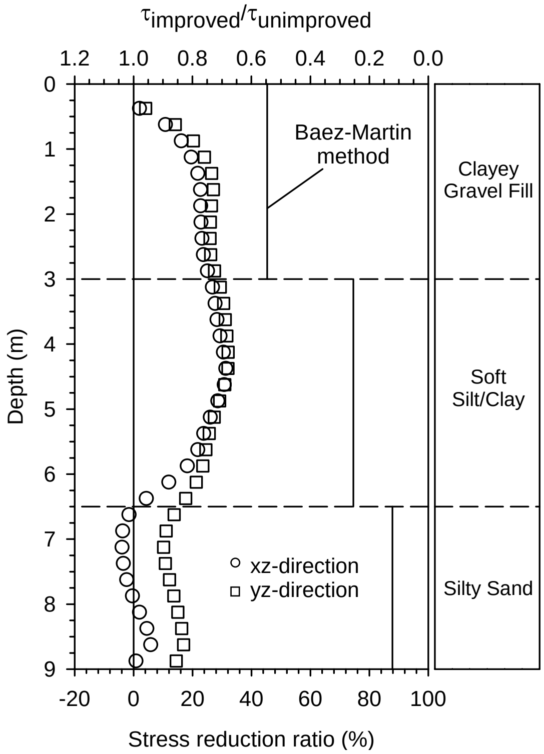

Figure 7. Shear stress reduction ratio; 3D analysis results compared with Baez-Martin design method

of this strain compliancy, the stiff column carries more shear stress than the soil, in proportion to the shear moduli of the column and the soil (i.e. $\tau_{column}/\tau_{soil} = G_{column}/G_{soil}$). Average values of the peak shear strains within the jet-grout column and the surrounding soil are presented in Figure 8. As can be seen, the stiff columns were not strained as hard as the soil around them. They experienced negligible shear strains, while peak strains in the reinforced soil mass approached 1%. The analyses suggest significant strain incompatibility between the soil and columns which were about 50-150 times stiffer in shear relative to the soil. A closer look at the relative values of the shear strains within the soil and the jet-grout column is given in the next panel where the ratio of the shear strain within the column and soil is presented. It can be seen that the soil is being strained in the range of 6-250 times harder than the soil along the improved profile. Such strain incompatibility was also evident in the deformed mesh shapes, which showed that the columns tended to flex back and forth within the soil profile and rotate at the ends during shaking rather than shearing along with the surrounding soil. A schematic of the column and soil deformation is shown in Figure 9. In essence, the columns underwent mainly flexural deformations as opposed to shearing deformations. As such, they clearly did not behave as shear beams with the soil profile to any significant degree during shaking, as tacitly assumed. Therefore, even though the columns were much stiffer, they did not strain sufficiently in shear to attract a significant portion of the shear loading. This means the columns should not have significantly reduced shear strains, and thus excess pore pressures, in the soil mass as initially thought.

DISCUSSION AND CONCLUSIONS

We feel this case study is particularly instructive because the approach of using closely-spaced jet-grout columns to mitigate liquefaction differs from the common practice of constructing rows of contiguous columns to form cells to contain liquefied material. This is the first documented case where this approach has been tested during strong ground shaking. And although it was clear that the ground treatment was effective, the numerical analyses show that the seismic behavior of the reinforced ground and the primary reason for its effectiveness was different than suggested by common analytical approaches.

The numerical results revealed important insight into the seismic behavior of the reinforced ground. The common assumption is that the ground reinforcement using stiff columns results in significant stress reduction due to the implicit assumption that the ground will behave in a composite fashion. This implies the stiff columns will attract most of the load and reduce shear stresses and strains in the soil mass. As revealed in the numerical analyses however, composite behavior was an invalid assumption, as the columns and soil were undergoing different modes of seismic deformation. For the most part, the columns did not deform in shear during shaking. Instead, the results indicate that they behaved primarily as flexural beams and did not attract a significant portion of the seismic shear loading. This means the columns did not behave as shear beams to any significant degree and did not significantly reduce stresses. This finding is generally consistent with results reported by Goughnour and Pestana (1998) based on their analysis of ground reinforced with stone columns. They found that the columns should provide little, if any, shear stress reduction in most cases.

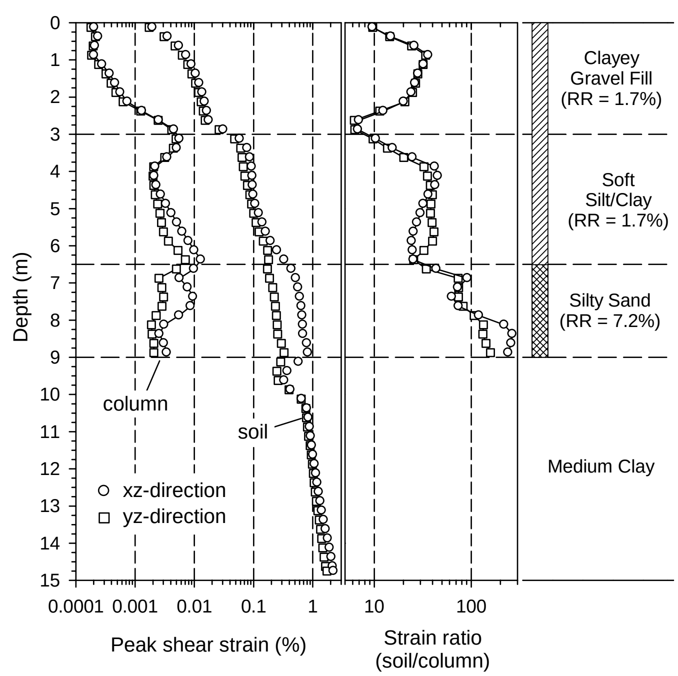

Figure 8. Comparison of the peak shear strains within the jet-grout column and the soil

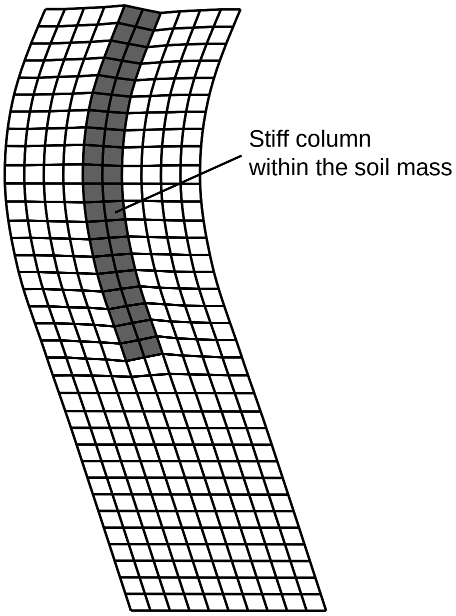

Figure 9. Stiff column deforming in flexure

We feel the main implication is that commonly-used design approaches based on assumptions of composite behavior for ground reinforced with discrete elements may greatly overestimate seismic improvement in terms of shear reduction behavior. At the time of this writing, detailed parametric studies of columnar reinforcement are being performed to better understand the effects of reinforcement stiffness, geometry and layout, end-restraint conditions, etc. and to establish general behavior trends.

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

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