GROUND MODIFICATION: HOW MUCH IMPROVEMENT?

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ABSTRACT: Ground modification has been used on many construction sites to densify granular material and reduce potential settlement or the susceptibility to liquefaction. This paper evaluates the benefits derived through several ground improvement methods, deep dynamic compaction, vibro-compaction, and vibro-replacement. These ground modification procedures were performed on several study sites with the effectiveness of the methods evaluated by comparing the tip resistance of pre- and post-construction cone penetrometer test (CPT) soundings. The results provided by the treatment methods were also evaluated with respect to the amount of fines observed in the subsurface profile. The results of our evaluation are intended to expand the availability of information on the effectiveness of these ground modification methods.

INTRODUCTION

A successful ground modification project can be defined as one that achieves the anticipated improvement with the proposed technique. However, since there is always a level of uncertainty in defining the subsurface conditions, and the success of a ground improvement program depends on how the soil conditions respond to a specific technique, generally some type of verification testing is performed during construction. This case history paper describes our experience with the densification obtained by three ground improvement methods: 1) vibro-replacement, 2) vibro-compaction and 3) deep dynamic compaction. These ground modification procedures were performed on several study sites with the effectiveness of the methods evaluated by comparing the tip resistance of pre- and post-construction cone penetrometer test (CPT) soundings.

Of particular interest to the authors was the correlation of ground modification benefit to the amount of fines in the subsurface profile. It is the authors' intent to expand the available information with respect to the amount of improvement obtained from various ground modification methods.

GROUND MODIFICATION TECHNOLOGIES

The ground improvement methods compared within this study include: 1) vibro-replacement, 2) vibro-compaction and 3) deep dynamic compaction. A brief description of each process as well as its applicability is presented below.

Vibro-compaction

Vibro-compaction is a process in which a large, cylindrical vibrator, suspended from a crane, is inserted into a soil profile with the intent of compacting the surrounding soil. The vibrations are induced by an eccentric mass rotating in a horizontal plane. The vibrator is lowered to the desired treatment depth under its own weight or with the aid of jetting. The resulting annular void around the vibrating probe as well as the void created during removal is backfilled from the surface with a clean sand fill. The process is typically used to densify relatively clean, cohesionless sands with silt contents generally less than 12 to 15 percent and/or clay contents less than 3 percent (Schaefer, 1997). Normally, the probe is inserted in a uniformly spaced grid pattern. This technique primarily achieves densification through the material's response to vibration.

Vibro-replacement

Vibro-replacement is similar to vibro-compaction and uses the same equipment. However, rather than relying solely on vibrations for densification, vibro-replacement uses a relatively clean stone for backfill rather than sand. As the stone fill is placed in the annular space and removal void, the vibrator is reinserted into the stone, thereby forcing the stone into the adjacent soil, forming a stone column. The combination of vibration and displacement of looser soils by the relatively incompressible stone is used to densify the surrounding soils. Vibro-replacement is typically used to densify soils that are too "dirty" for vibro-compaction: non-cohesive materials having a fines content of less than 15 to 25 percent (Xanthakos, et al, 1994). The vibro-replacement process creates a stone column, which provides reinforcement in addition to densification. This additional improvement mechanism (i.e., reinforcement) is not relevant to the scope of this paper.

Deep Dynamic Compaction

Deep dynamic compaction (DDC) is one of the most economical ground modification methods. This technique involves repeatedly dropping a large weight from a crane in a grid pattern to densify the underlying materials. The weight may range from 6 to 25 tons and the drop height typically varies from 12 to 20 meters. The repeated impact of the high energy mass can densify loose sands to depths of 3 to 8 meters. The degree of densification achieved is a function of the energy input (i.e., weight and drop height) as well as the saturation level, fines content and permeability of the material. DDC is not appropriate for saturated clayey soils.

METHODS FOR MEASURING IMPROVEMENT

Many field test methods have been used to evaluate the effectiveness of densification-based ground improvement methods. The performance of Standard Penetration Tests (SPT's) and Cone Penetrometer Tests (CPT's) are the most commonly employed field verification methods and provide an estimate of in situ soil relative density. A direct estimate of densification improvement can be obtained by comparing pre-and post-construction SPT "N" Values or CPT tip resistances. Using CPT tip resistances (q_c), Dove et al. (2000) defined an improvement index, $I_{d,}$ as:

$$I_d = \frac{q_{c,after}}{q_{c,before}} - 1 \tag{1}$$

As discussed by Schaefer and White, 2004, this improvement index could alternatively be based on any in situ quality control measurement technique, where a specific soil property is measured before and after the improvement method over a specific zone of interest.

Although useful for comparison purposes, the improvement index does not explicitly account for factors that are known to influence the degree of improvement. For example, it has been shown that the amount of densification is related to the spacing of the treatment grid (or similarly, the diameter of the stone columns) as well as the silt/clay content (Fang, 1991, after Wallays, 1982). Hussin and Ali (1987) reported that no appreciable improvement was obtained with vibro-technologies when the fines content exceeded 12 percent. Additionally, the degree of improvement is more sensitive to the quantity of the clay-size fraction than it is to the silt-size fraction.

For the purpose of this study, we adopted the improvement index as defined by Dove et al. (2000) but we have also tried to explicitly account for the fines content effects on the degree of improvement. More specifically, the approximate fines content of the subsurface profiles was estimated directly from the pre-construction CPT results using the soil behavior type index combined with the relationship between fines content (FC) and friction ratio as presented in Lunne, et. al. (1997). This relationship is simplified to the following:

$$FC\% = 1.75 * I_c^3 - 3.7 \tag{2}$$

where: $I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 1.22)]^{0.5}$
Q_t = normalized penetration resistance (dimensionless)
F_r = normalized friction ratio (percent)

For several cases, the approximate fines content estimated from the CPT data were compared with laboratory test results. In general, the CPT fines content computed using Equation 2 correlated relatively well with the laboratory test results.

GEOLOGY OF CASE STUDY SITES

The case study sites were located within the Atlantic Coastal Plan Physiographic Province near Charleston, South Carolina. This Province is comprised of upper sediments composed of Quaternary and Pleistocene age deposits underlain by the Cooper Group of the Tertiary period (Horton and Zullo, 1991). The sediments within the Charleston area are typically 10 to 25 meters thick and are primarily comprised of interbedded sands, silts and clays. The Cooper Group is generally an overconsolidated, calcareous silt that is typically more than 60 meters thick in this area. The location of each of the case study sites is shown in Figure 1.

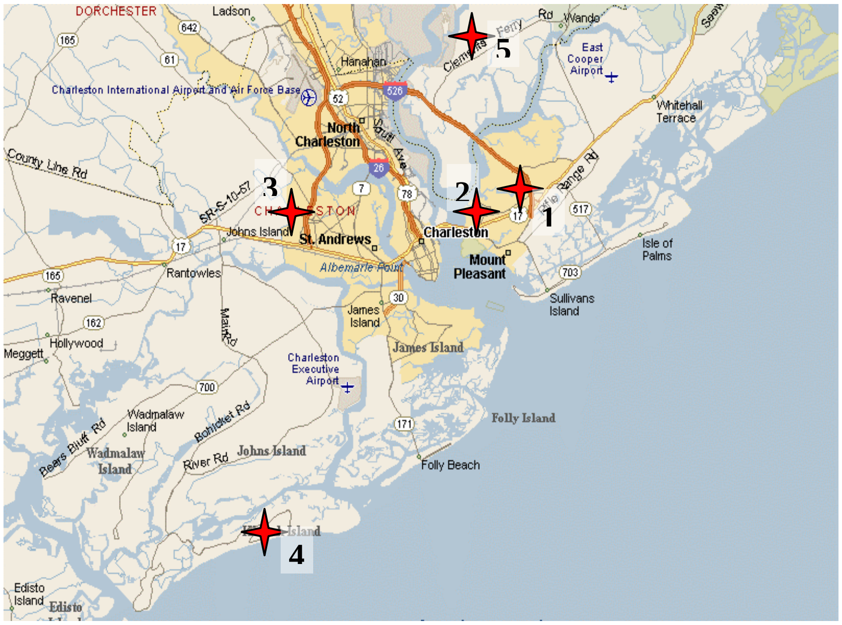

Figure. 1 Case Study Locations

Table 1. Summary Information

Identification	Generalized Profile	Method	Treatment Depth	Treatment Pattern	Backfill	Laboratory Fines Content
Case 1 – Hwy 17	0-2 m, silty sand; 2-8.5 m, sand	V-C	8.5 m (28 ft)	2.4 m square (8 ft)	Sand	5% @ 2.3 m; 6% @ 4.6 m; 8% (4% clay) @ 6.1 m; 3% @ 7.6 m
Case 2 - Bridgeside	0-2 m, sand; 2-4 m, silty sand; 4-6 m, sand	V-C	6.1 m (20 ft)	2.4 m square (8 ft)	Sand	5.9% (<2% clay) @ 0-2 m; 10%-16% (6%-8% clay) @ 3-6 m; 4.5% (<2% clay) @ 4.5-5.5 m
Case 3 – West Ashley	0-1.5 m, sand; 1.5-3 m, silty sand; 3-7 m, clayey silt; 7-9 m, silty sand	V-R	8.5 m (28 ft)	2.4 & 2.7 m square (8 & 9 ft)	19mm clean stone	n/a
Case 4 - Kiawah	0-6 m, sand; 6-8.5 m, silty sand	V-R	8.5 m (28 ft)	2.4 & 2.7 m square (8 & 9 ft)	19mm clean stone	42-44% @ 7.5 to 9 m
Case 5 - Cainhoy	0-7.5 m, sand; water table @ 4.6 m	DDC	n/a	9 ton; 17 m (55 ft) drop height; 2 passes	n/a	n/a

V-C=vibro-compaction; V-R=vibro-replacement; DDC=deep dynamic compaction

At each of the case study sites, the specific subsurface conditions were determined prior to construction using cone penetrometer test soundings and soil borings. Following ground improvement, post-construction soundings were obtained at each site. The post-construction soundings were always performed near the center of treatment grid and should therefore yield a conservative estimate of the degree of improvement. More specific details associated with each case are presented in Table 1.

CASE STUDY RESULTS

Cases 1 and 2: Vibro-Compaction

At Case study sites 1 and 2, the vibro-compaction program generally improved granular materials with less than 10 percent fines as indicated by the improvement indices, I_d, shown in Table 2 and CPT results shown in Figures 2 and 3. The lower improvement index values in Case 1 for a zone with less than 5 percent fines is likely due to the relatively high pre-construction CPT tip resistances, about 15 MPa. In Case 2, the results indicate that the densification of the materials was reduced in the zone between 2.3 to 4.3 m, which generally has a similar CPT fines content as the remaining profile. However, laboratory hydrometer testing on material obtained from this zone indicated that the clay content was about 7 percent versus < 2 percent in the remaining portion of the profile. In addition, an appreciable gain in densification was also noted within the layers that had a larger fines content but a lower pre-construction CPT tip resistances, typically < 5 MPa. In general, the amount of densification improvement decreased with increasing fines content.

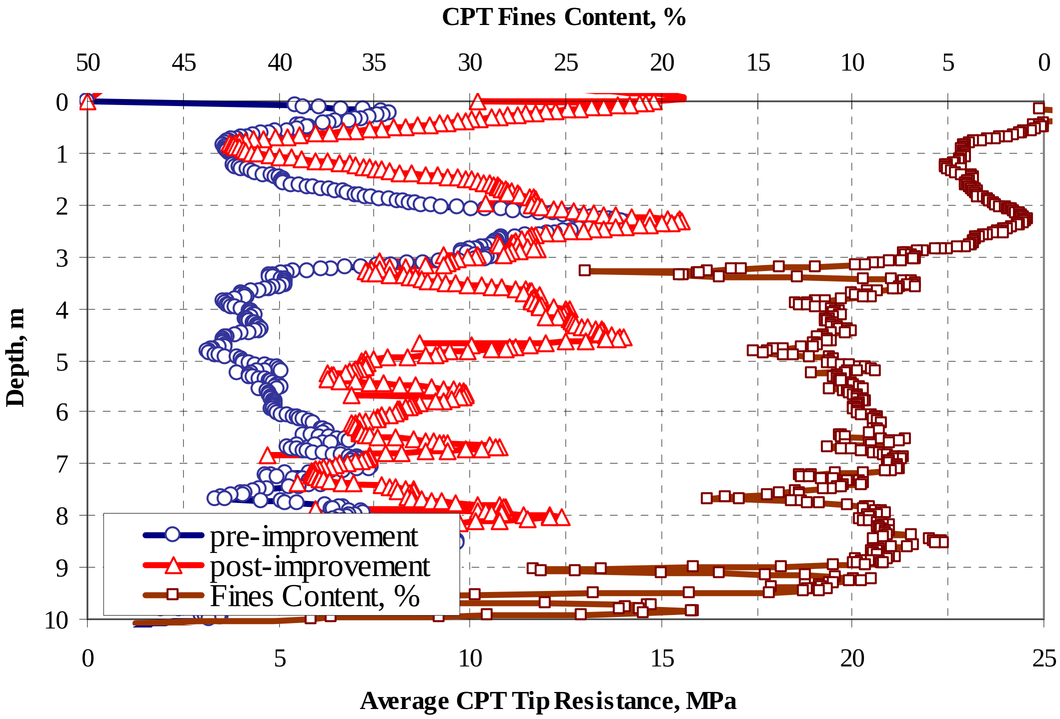

Figure 2. Case Study No. 1: Highway 17 Site

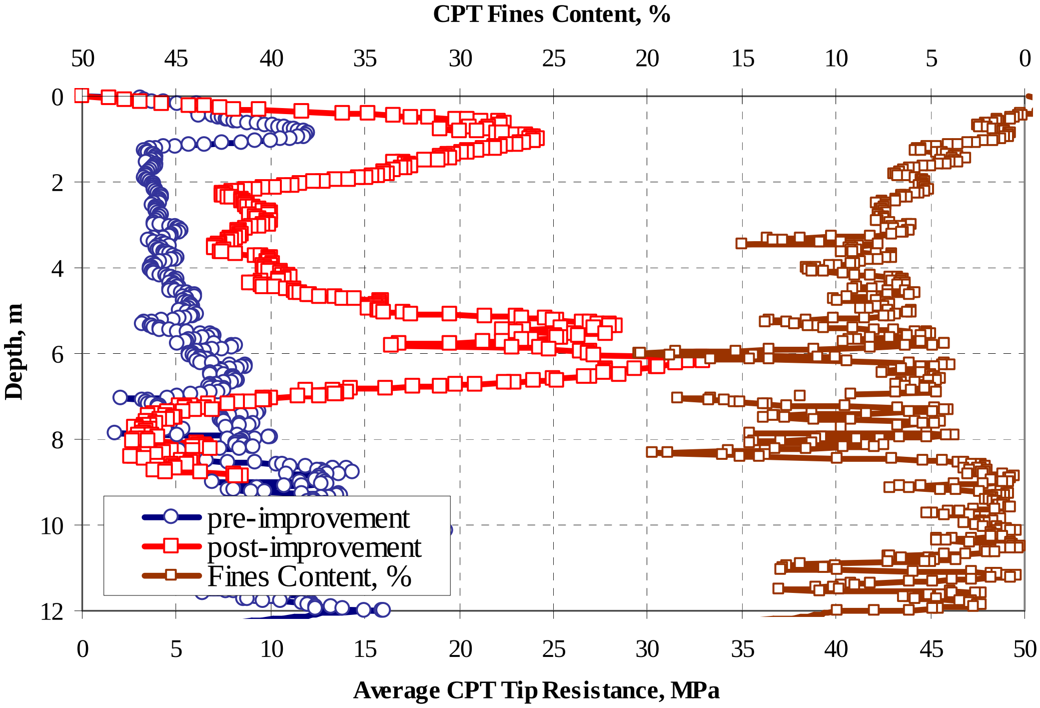

Figure 3. Case Study No. 2: Bridgeside Site

Table 2. Improvement Index – Cases 1 and 2: Vibro-Compaction

CPT Fines Content, %	Improvement Index, I_d	
	Case 1	Case 2
< 5 %	0.3 – 1.0	0 – 1.5
5-10%	0.5 – 0.7	1 – 3*
10-15%	0 – 2.0*	1.4 – 2*
> 15%	0 – 0.2*	0 – 0.5*

*Improvement Index on material with pre-construction tip resistance of < 5 MPa

Cases 3 and 4: Vibro-Replacement

The modification indices, I_d, shown in Table 3 and CPT tip resistance shown in Figures 4 and 5 indicate that vibro-replacement densified the materials with a fines content of < 5 percent. As the fines content increases, the amount of densification decreased except within zones that had low pre-construction tip resistance of < 5 MPa.

Table 3. Improvement Index – Cases 3 and 4: Vibro-Replacement

CPT Fines Content, %	Improvement Index, I_d	
	Case 3	Case 4
< 5 %	0.3 – 2.8	1.5 – 2.7
5-10%	0.2 – 0.8	0.4 – 1*
10-15%	0 – 0.2	0.2 – 1*
> 15%	0 – 0.2	0 – 1.6*

*Improvement Index on material with pre-construction tip resistance of < 5 MPa

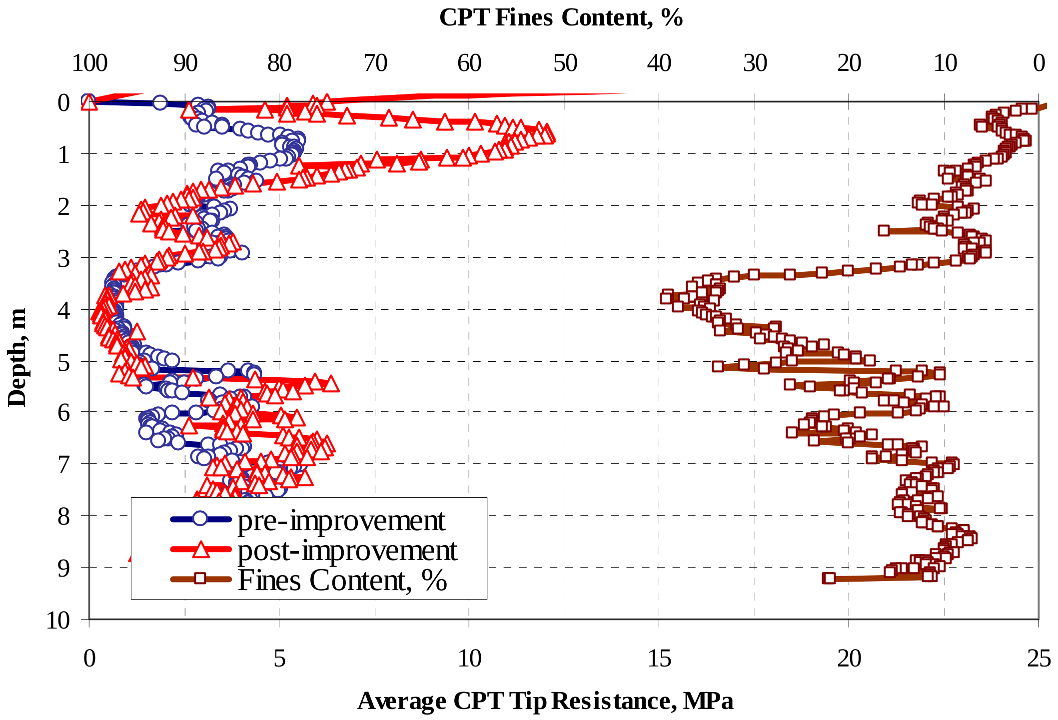

Figure 4. Case Study No. 3: West Ashley Site

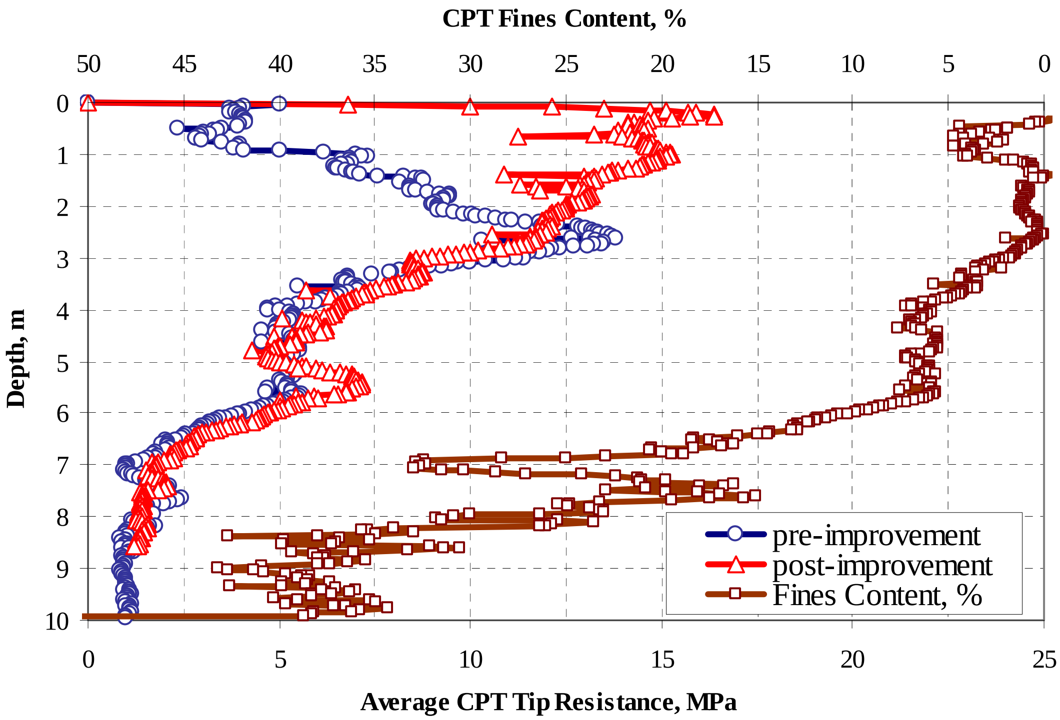

Figure 5. Case Study No. 4: Kiawah Site

Case 5: Deep Dynamic Compaction

The Case 5 study site results, as shown in Table 4 and Figure 6, indicate that fines at contents below about 15 percent do not influence the densification improvement resulting from deep dynamic compaction. The amount of densification is more influenced by the position of the groundwater table. As seen in Figure 6, the increase in post-construction tip resistance reduces to almost no improvement below a depth of 4.3 m, which is about the measured level of groundwater.

Table 4. Improvement Index – Case 5: Deep Dynamic Compaction

CPT Fines Content, %	Improvement Index, I_d
	Case 5
< 5 %	0.7 – 1.2
5-10%	0.7 – 1.7*
10-15%	0.6 –1.2
> 15%	NA

*Improvement Index on material with pre-construction tip resistance of < 5 MPa

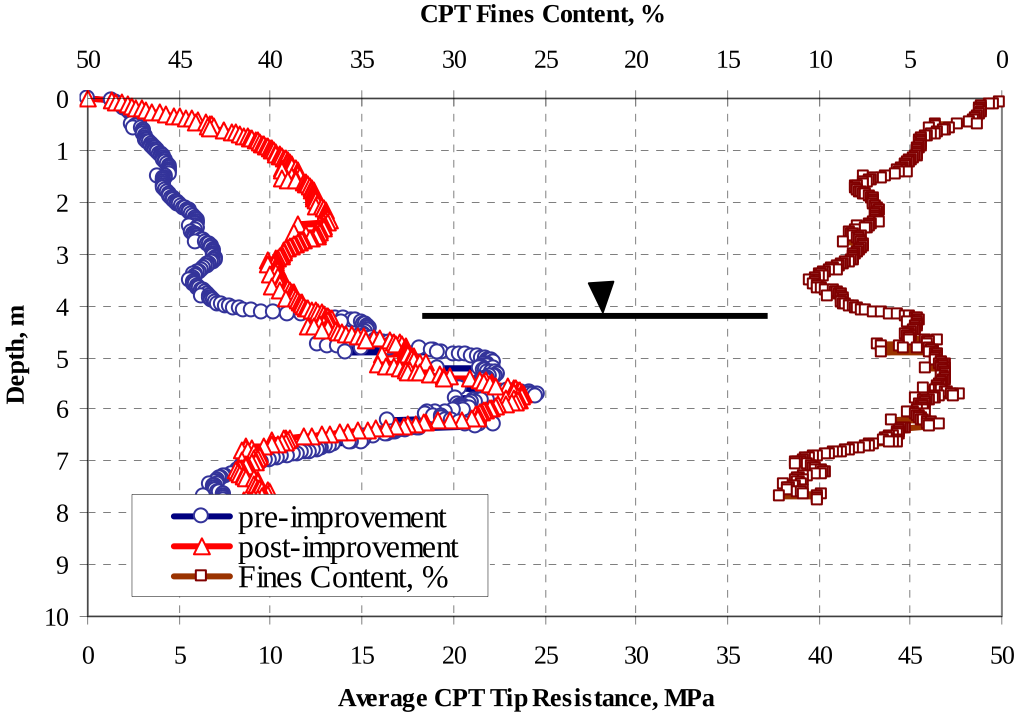

Figure 6. Case Study No. 5: Cainhoy Site

CONCLUSIONS

The results of the case studies indicate the densification achieved from vibro-compaction and vibro-replacement is a function of the initial density and fines content of the material. As the fines content increases, the densification improvement generally decreases. Also, Case Study Site No. 2 suggests that not only does the fines content affect the densification improvement of vibro-technologies, but also the type of fines (i.e., clay versus silt), affects the densification performance.

Case Study Site No. 5 suggest that the deep dynamic compaction process is not as influenced by the fines content of the material. However, it should be noted that the majority of the materials densified by this process in the study had a fines content of less than 10 percent. Additional study should be performed at other sites to verify this conclusion.

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