

Deep dynamic compaction and preloading to facilitate shallow foundations

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ABSTRACT: A detailed subsurface investigation at a site along the Cooper River, a tributary to the Delaware River in Camden, New Jersey revealed two subsurface factors which would both contribute to intolerable settlement if shallow foundations were to be used: nearly 20 ft of loose, existing fill and 15 to 20 ft of soft, normally to slightly overconsolidated, high plasticity silt. Based on consolidation tests on the soft silt, we developed a two-step ground improvement program which would enable the use of conventional shallow foundations without the need for costly piles. This approach comprises deep dynamic compaction (DDC) to densify the existing loose fill and preloading to induce consolidation of the underlying soft silt prior to construction. The DDC, in addition to densifying the loose fill, increased the buildup of the excess pore water pressure in the silt and enhanced the performance of the preloading program beyond what would have been possible by a 6 ft surcharge alone. This was confirmed by installing drive point piezometers into the middle of the soft silt at selected locations across the building footprint to gauge the increase in excess pore water pressure due to the DDC operation. After completing the DDC, sensors were installed to monitor the settlement of the surcharge and determine when it can be safely removed. The combination of DDC and preloading were essential for the success of this ground stabilization.

KEYWORDS: Deep Dynamic Compaction (DDC), preloading, compressible soils, loose fill, shallow foundations, instrumentation.

1 INTRODUCTION

Since its development by Menard (1975), deep dynamic compaction (DDC) has been widely implemented and well documented for remediation of loose sand deposits, mine spoils, urban fills and demolition debris, and municipal solid waste landfills (e.g., Chow et al. 1992; Steinberg and Lukas 1984; Lukas 1995, Woods et al. 2023). The method works by collapsing subsurface voids, increasing the packing of the individual grains, and reducing the compressibility of the soil mass. A key advantage of DDC, beyond its significant stabilization depth of influence, is that its performance is largely independent of the soil's water content, provided the soil has high permeability and good drainage. However, this limits its use to subsurface conditions with predominantly granular soils. Of the 124 case studies compiled by Mayne et al. (1984), only 27% had silt, clay, or silty clay soils.

The development of coastal areas in China has sparked a combination of DDC with preloading or vacuum dewatering for improving soft compressible soils and dredge spoils (e.g., Feng et al. 2014; Chang et al. 2010; Deng and Xu 2010). In cases involving layered soil profiles or insufficient strength below the depth of DDC's influence, additional ground improvement is often needed to achieve adequate results. Past documented projects have paired DDC with compaction grouting or stone columns to densify both shallow and deeper soil layers, as summarized by Mitchell and Welsh (1989). Still, the literature remains limited on the adaptation of DDC with other ground improvement methods for layered and compressible soils. This paper presents a case study in which DDC was used in conjunction with preloading to induce consolidation of soft silt below a thick layer of loose fill to facilitate construction of a 5-story office building on conventional shallow foundations. The DDC, in addition to densifying the historic, loose fill, expedited the removal of the surcharge by increasing the buildup of excess pore water pressure in the underlying silt layer.

2 INVESTIGATION AND DESIGN

2.1 Existing Site Conditions

This Philadelphia area site is located approximately one mile east of the Delaware River bank, near the Cooper River's

confluence with the Delaware River back channel. In general, very thick sands and gravels of marine origin overlie the very deep basal rocks. However, along the Delaware and Cooper Rivers, a much younger floodplain deposit of sand, gravel, silt, and clay forms the flat lands, also called mud-flats, closer to the banks. The swampy ground within the Cooper River floodplain was filled with soil mixed with demolition debris, ash, slag, and glass, according to a historic fill map of the Camden Quadrangle (Stanford 2004).

2.2 Field Exploration and Subsurface Characterization

Test borings were conducted to depths between 70 to 100 ft below existing grade. Standard penetration test (SPT) sampling was carried out at regular intervals in all borings and the SPT *N* values recorded. Thin-walled Shelby tube samples were also obtained in the soft, river silt deposits. Furthermore, tip resistance (q_t) and sleeve friction (f_s) from cone penetration tests (CPT) were recorded continuously together with their ratio. The soils were classified and given a group name based on the Unified Soil Classification System (USCS). The subsurface characterization was idealized for design as summarized in Table 1 along with SPT and CPT data.

Table 1. Idealized Subsurface Characterization.

Depth	Soil Description (USCS)	Water Content	SPT (<i>N</i>)	CPT (q_t psf)
0 – 20 ft	Historic Fill (SM, GW)	24.7%	3-50+	20-400+
8-20 ft	Alluvium (SM, SP)	-	2-15	20-50
15-34 ft	Alluvium (MH, OH)	70.8%	4-11	10-15
30-70 ft	SM, SP, SC, & lightly OC ML, MH, OH	29.5%	10-30	15-150
70+ ft	Alluvium (CL)	-	15-59	50-100

The erratic and abnormal *N* values and tip resistances measured in the historical fill layer are attributed to buried concrete and rock obstructions and remnant building elements common throughout this layer. The soft high plasticity and organic silt between 15 and 34 ft in depth has some lamination and interlayering with poorly-graded sand sublayers and plant debris suggesting a cyclic, and relatively calm paleo-depositional environment. Index tests as well as unconfined

compressive strength, and 1-D consolidation were performed on samples from this compressible silt layer. A summary of the laboratory test results including the virgin and rebound slopes, C_c and C_r is presented in Table 2. The measured coefficient of consolidation, C_v , varied between 0.1 to 0.2 ft²/day.

The CPT results depicted a phreatic groundwater surface between 9.5 and 12.8 ft below existing grade. Wet soils detected during SPT sampling, however, were encountered at depths of 6 to 8 ft below existing grade, likely higher due to capillary action. At this site, the water table will vary based on tidal fluctuations of the Delaware River. A schematic portrayal of the soil and groundwater conditions is presented in Figure 1.

Depth	Density (pcf)	Water Content	UCS (ksf)	OCR	C_c	C_r
26.3 ft	101.0	50.7%	0.92	1.2	0.39	0.06
26.6 ft	106.0	48.6%	-	1.0	0.40	0.06
18.6 ft	87.5	91.5%	2.46	1.8	0.80	0.10
20.6 ft	97.4	64.7%	1.51	1.8	0.69	0.07
21.5 ft	89.2	86.8%	1.27	1.7	0.93	0.11

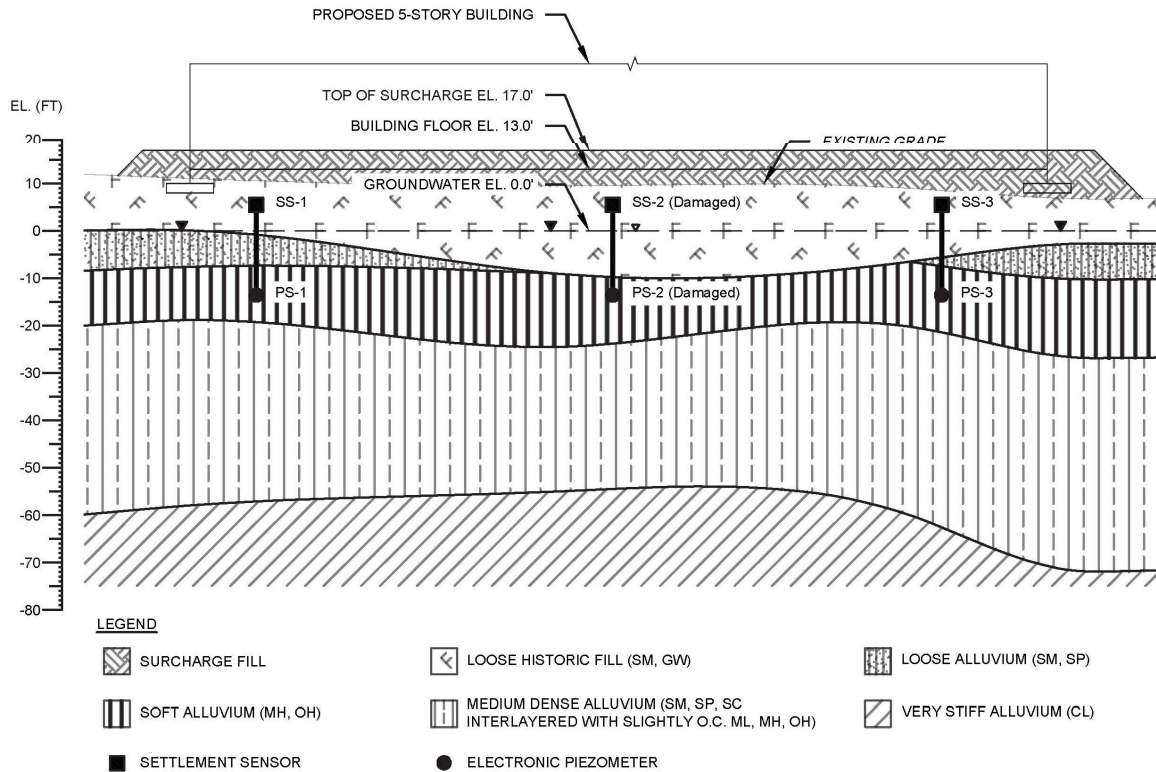


Figure 1. Idealized Subsurface Section

2.3 Foundation Selection

Aside from the loose fill and its erratic composition being obviously unsuitable for supporting shallow foundations, the high plasticity and organic silt will consolidate under as much as 6 ft of new fill and the building loads. A total consolidation settlement of 4 in. was calculated if the building were to be constructed without any ground improvement. Preliminary pile designs required minimum lengths of 60 to 80 ft to achieve necessary capacity and costly pre-drilling through the many buried obstructions would also be required. Also, a structural slab supported by piles or a surcharging program would be needed for construction of the building ground floor.

These issues made the pile foundation option cost prohibitive. Consequently, it was decided to combine DDC and preloading in order to improve the historic fill for direct support of shallow foundations and limit the long-term consolidation settlement of the underlying soft silt deposits.

The DDC program was designed using an 8-ton weight dropped from a height of 40 ft, resulting in a minimum energy

of 320 ton-ft per drop. The work was intended to be completed in one pass with 8 ft spacing and 7 drops per location. The calculated depth of improvement was 18 ft. Preloading was designed for 6 ft of fill above existing grades (4 ft higher than the finished floor) for a duration of 16 weeks to induce a minimum of 2.5 in. of settlement and maintain the long-term building settlement within tolerable limits. It was to intended take place immediately after completion of DDC. This combined ground improvement approach allowed the new building to be supported by conventional shallow foundations, sized for an allowable bearing pressure of 6,000 psf.

3 CONSTRUCTION MONITORING AND INSTRUMENTATION

3.1 Deep Dynamic Compaction

A test section for DDC was first implemented to confirm the performance of the program as intended. Before and after spot elevations a grid basis were selected as the primary means of performance tracking. An induced ground settlement of 1.5 ft, roughly 7-10% of the thickness of the historic fill, was specified

as a performance criterion. After completion of the test section, the DDC program was slightly adjusted by increasing the number of drops to 8 per locations and reducing the spacing between drops to 7 ft to achieve the intended objectives.

At the start of construction, three electronic, drive-point piezometers were installed between 20 and 30 ft below existing grade and were all set within the soft, high plasticity and organic silt layer as shown schematically in Figure 1. However, PS-2 was damaged and PS-3 turned out to coincide within a free-draining sand lens sublayer of the soft silt deposit. DDC immediately followed the installation of the piezometers and lasted for 4 weeks, progressing from right to left in Figure 1.

Specifically, DDC occurred over PS-3 during week 1 and over PS-1 toward the end of week 4.

3.2 Preloading

After completing DDC, three settlement sensors were installed at locations accompanying the piezometers before starting to place the surcharge fill. The surcharge was placed in 1 ft thick lifts and compacted with a heavy-duty, smooth-drum roller. The fill material consisted of well-graded sands and gravels with an average maximum dry density of 125 pcf. The first lift was placed at the start of week 5 and the operation, which slowed down due to weather, was completed during week 7 as illustrated in Figure 2a. In total, 6 ft of fill was placed.

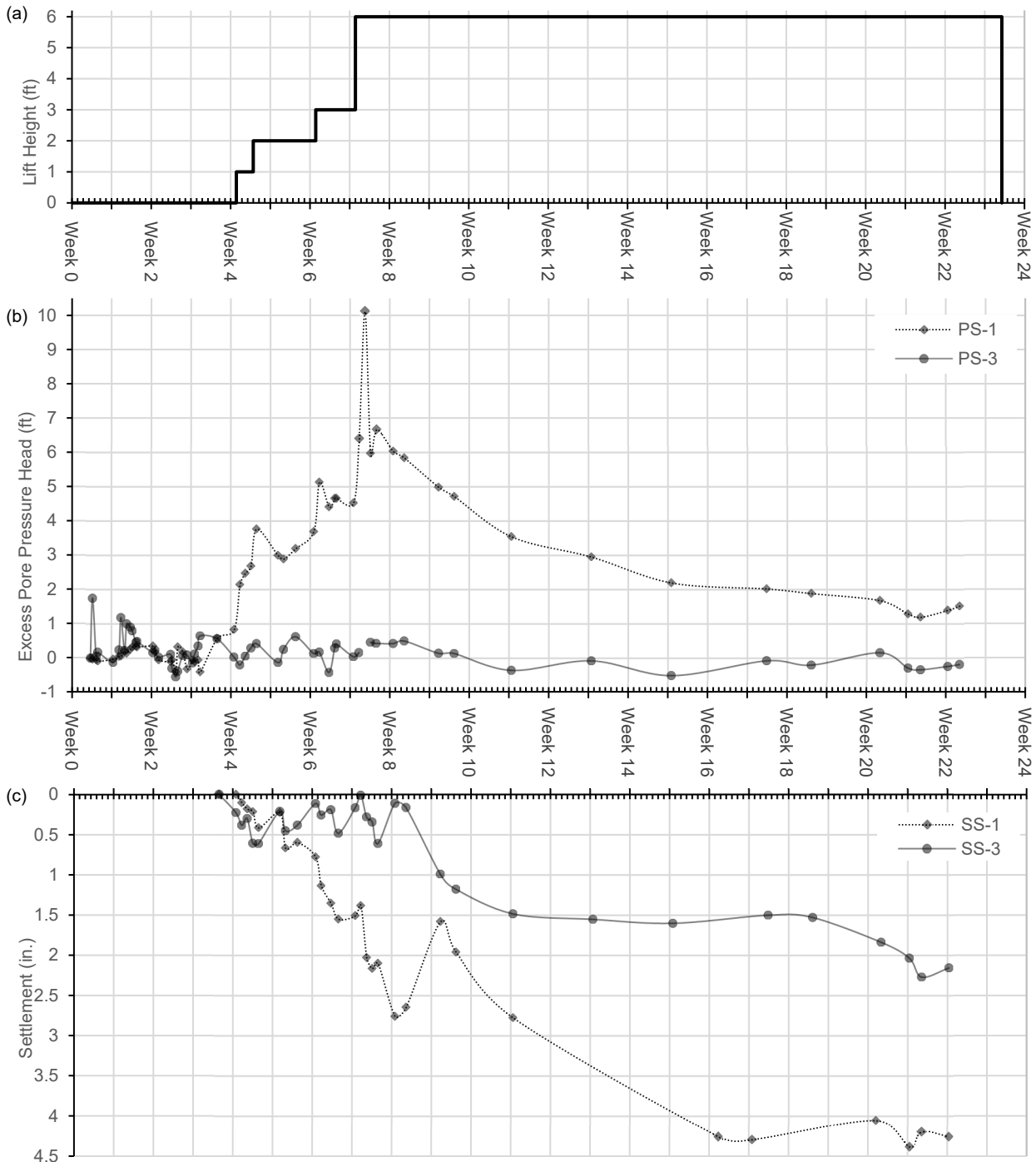


Figure 2. (a) Lift height vs. construction schedule; (b) excess pore pressure head vs. construction schedule; (c) settlement vs. construction schedule.

4 ANALYSIS & DISCUSSION

Figures 2b and 2c show the excess pore pressure and settlement plots versus time from the start of DDC through the completion and removal of the surcharge. During the 4 weeks needed to complete DDC, the excess pore pressure head spiked to approximately 3 ft in PS-1 and 2 ft in PS-3. These excess pressures quickly dissipated in PS-3 with some dissipation occurring in PS-1 prior to surcharging. Evidently, this is due to PS-3 coinciding within a free-draining sand lens in comparison to PS-1 in the high plasticity silt.

Following DDC, the surcharge fill was placed during a period of three weeks as shown in Figure 2a. The excess pore pressure continued to build up until reaching a maximum value of 10 ft in PS-1 at the completion of the fill placement. As expected, the excess pore pressure in PS-3 continued to quickly dissipate following the placement of each lift of fill.

The corresponding settlement is shown in Figure 2c. Within a period of two to three weeks of completing the surcharge placement, SS-3 settled 1.5 in. then leveled off shortly thereafter. This is consistent with the higher dissipation measured in the piezometer at this location. Conversely, SS-1 continued to settle through week 16, levelling off at about 4.5 in. It is noted that the fill was temporarily stockpiled near SS-1 at the end of week 6. This resulted in a spike in the excess pore pressure with increased settlement and a corresponding rebound in weeks 8 and 9 after the stockpile was removed to complete the surcharge placement.

A careful examination of Figure 2 reveals the contribution of DDC to the consolidation settlement of the high plasticity silt due to increasing the buildup of the excess pore water pressure. As can be seen, the pressure head in PS-1 is 3 ft at the start of the surcharge placement and 10 ft at its completion (Figure 2b). Considering a DDC pressure distribution within the silt layer to have a maximum value at the top and to diminish linearly toward the bottom, the corresponding contribution to degree of consolidation can be calculated and compared to that due to the surcharge alone. This is obtained by dividing the triangular area of the DDC induced pressure distribution by the initial rectangular distribution associated with a surcharge on a double-drainage consolidating layer. As a result, the DDC contributes one-third of the consolidation settlement of the soft silt layer in addition to its primary benefit of densifying the loose overlying fill. Evidently, the surcharge alone would have only removed two-third of the total consolidation settlement for this project and either a larger surcharge or a longer duration would have been necessary to remove 4 in.

5 CONCLUSIONS

This paper illustrates the effectiveness of combining DDC with preloading to stabilize a layered subsurface profile comprising loose fill and underlying high plasticity silt. DDC, in addition to its traditional function of densifying loose fill, increased the buildup of the excess pore water pressure in the silt and enhanced the performance of the preloading program beyond what would have been possible by a 6 ft surcharge alone. For this case, DDC contributed about 33% to the overall consolidation settlement of the soft silt layer. It is noted though that this contribution would vary depending on the specifics of the subsurface profile, the DDC energy and the overall weight of the surcharge fill.

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