TECHNICAL PAPER

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UNIQUE CONTROL OF POST-CONSTRUCTION SETTLEMENT

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ABSTRACT

A new light rail system was to be located over a previously filled-in wetlands area. Although existing freight tracks crossed the area, construction of the passenger station would result in an increase in grades of 2 feet in the platform area and 9 feet in the parking area, which would induce additional settlement. Original settlement predictions were between 2 and 4.5 inches in the platform area, but as high as 24 inches within the parking area. Initial proposals were to install wick drains and surcharge throughout the entire site. However, as a result of construction priorities, the site was going to be used for stockpiles of excess soil from other portions of the project. Surface settlement monitoring points were installed throughout the site prior to build-up of the stockpile, taking advantage of any settlement that would occur due to the stockpiled material. This paper describes how this need for early storage of excess soil materials created the opportunity to use several different ground improvement methods for the control of post-construction settlement. Those methods included wick drains and surcharge where still required, the continued use of only surcharge, and low-density cellular concrete fill (LDCCF).

INTRODUCTION

The Route 73 Station for a new light rail line under construction between Camden and Trenton, NJ is located over a previously filled in wetlands area. The site for the passenger station is roughly rectangular in shape, with an existing freight track crossing the site parallel to the long axis. The new light rail alignment, which consists of both north and southbound tracks, essentially follows the alignment of the existing freight track.

The station consists of two platforms, the northbound platform (west of alignment) and the southbound platform (east of alignment), and a single parking lot (one of the largest for the project) located to the east of the station's platforms.

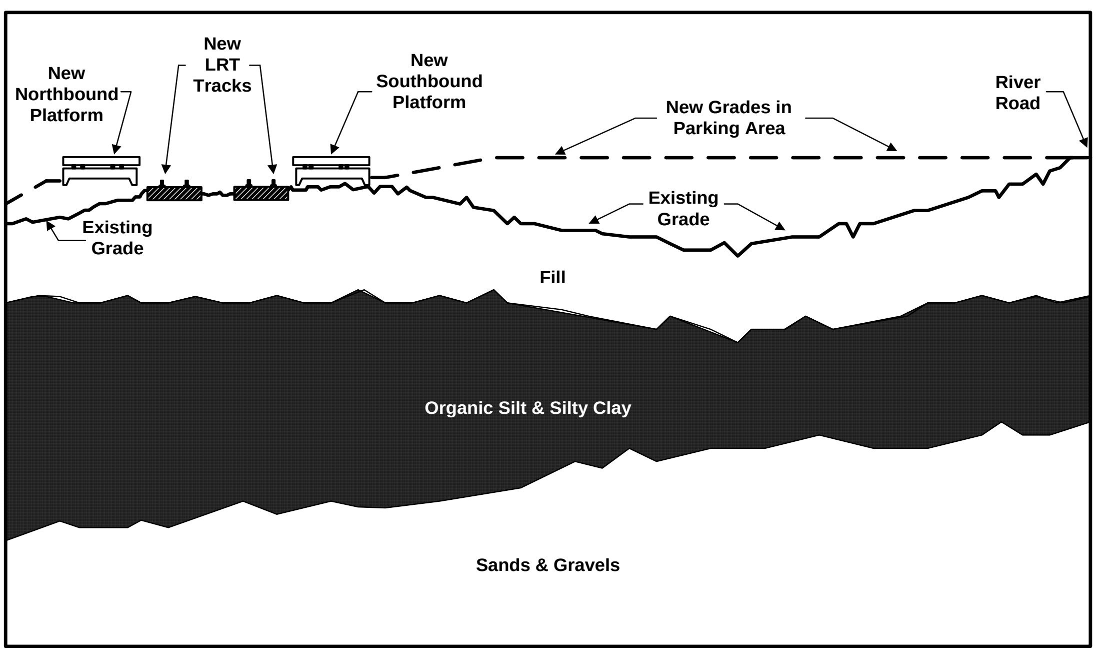
Prior to construction, site grades along the track alignment and within the area of the southbound platform were typically within 1 - 2 feet of proposed final grades. Site grades within the area of the northbound platform started within 1 foot of final grades at the edge of the tracks and then fell off to the wetlands (west of the site), such that the grades at the outer edge of the 12-foot wide platform were roughly 2.5 feet below the bottom of platform. Site grades within the parking lot ranged between 5 and 9 feet below final proposed grades.

SUBSURFACE CONDITIONS AND INITIAL SETTLEMENT ANALYSIS

The site is generally blanketed by 10 to 15 feet of granular fill with varying amounts of debris. Large boulders and debris had been used to fill in the wetland more than 20 years prior to present construction.

Underlying the fill is a layer of soft to very soft organic silt and silty clay. The thickness of this layer varied at the site—ranging between 15 and 20 feet at the eastern edge of the site, near River Road (the primary access to the site) to between 30 and 35 feet at the western edge of the site, near the proposed tracks (See Figure 1). Underlying this layer is a medium dense to occasionally very dense, fine sands and gravels.

Figure No. 1 – Section and Subsurface Profile at Route 73 Station



Laboratory tests on samples from the cohesive material at the site revealed the material to be normally consolidated. With the likelihood of the layer experiencing some virgin compression, initial settlement estimates were well in excess of acceptable limits (See Table 1). Although the estimates within the platform area were considerably lower than the parking area—due to the lower amount of fill, the settlement tolerances for the platforms were extremely stringent.

TABLE No. 1 – Initial Settlement Estimates

Area	Thickness of Clay Layer	Height of Fill	Est'd. Settlement	Coeff. of Cons. (c_V)*	Est'd. Time for 90% of Stlmnt. to occur
	(Feet)	(Feet)	(Inches)	(ft^2/day)	(Months)
Platforms Area	32 - 38	2 – 5	2 – 4.5	0.22	30 - 45
Parking Area	20 - 30	5	12 – 16.5	0.22	24 - 48
Parking Area	20 - 30	9	19 - 26	0.22	24 - 48

** - based on laboratory test results*

STOCKPILING AND SETTLEMENT MONITORING

With the expected settlements clearly in unacceptable ranges, several options were initially considered for minimizing post-construction settlement, including the installation of wick drains and soil surcharge, the use of lightweight fill, and the installation of piles. Since the general layout of the site was well suited to the use of wick drains and surcharge, and using piles would have necessitated a redesign of the precast platform panels, the plan selected was to use wick drains and surcharge over the entire site, both within the platform and the parking areas.

The proposed surcharge height needed to be at least 5 feet above final grades, and would remain in place for at least 6 months after installation of the wick drains were completed. The wick drains were to be installed in a triangular pattern with 5-foot spacings.

Due to the design-build nature of the project, the plan to use wick drains was still being developed as the construction phase of the project got underway. As construction began, the large parking lot quickly became a stockpile area for the growing amount of excavated material from other portions of the project. To take advantage of settlement that would be caused by the stockpiled material, a program was developed at short notice to monitor any on-going settlements.

The monitoring program included the installation of 13 monitoring points throughout the site, and exercising some minimal control of the height and placement of material. The minimum fill height was required to be maintained at proposed final grades, but the amount of additional surcharge placed above that level varied throughout the site and could not be controlled as easily during the monitoring period. The total amount of surcharge, however, was not critical since its primary purpose was to accelerate the anticipated settlement and not to simulate the anticipated loads. No material could be placed within the area of the platforms and rail alignment due to the requirement to keep the existing freight track operational.

Evaluation of Initial Settlement and Review of Predicted Settlement

Although much of the fill (up to proposed final grades) had been in place for longer, the monitoring program went on for about three months. Table 2 shows the estimated thickness of the cohesive layer at each monitoring point location, and the total settlement measured over the three month period. The settlement plots are shown in Figure 2.

In general, the settlements occurred as expected, with larger settlements being measured within the western portion of the site in areas of thick clay deposits and settlements less than 1 inch measured at the eastern portion of the site, near River Road. The maximum settlement measured was 10.13 inches at Monitoring Point # 10.

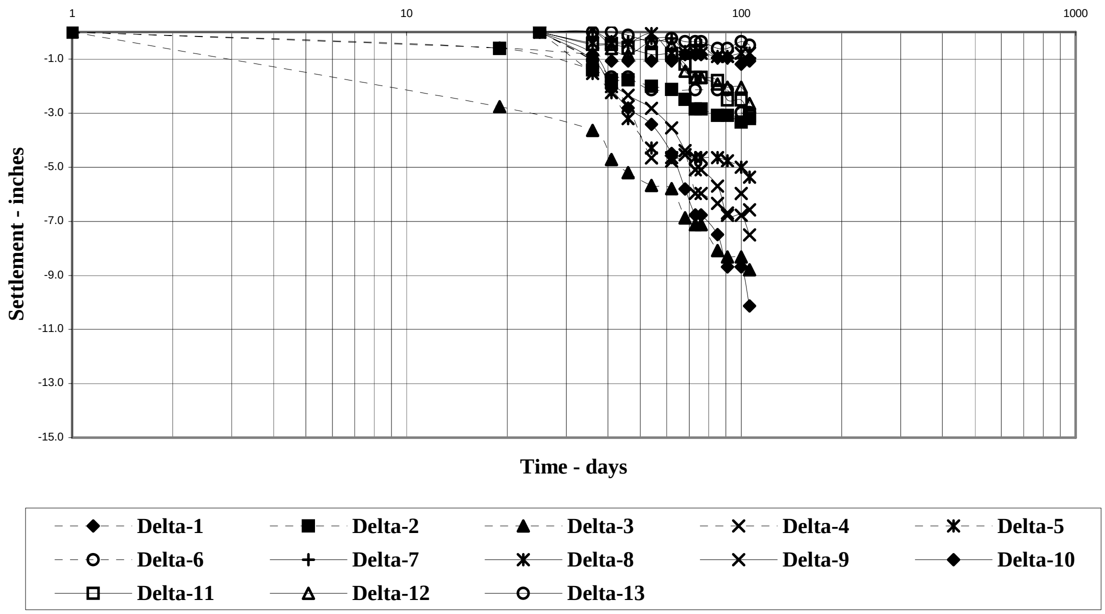
TABLE No. 2 – Total Measured Settlement at Monitoring Points

Monitoring Point	Estimated Thickness of Cohesive Layer	Monitoring Period	Total Measured Settlement
	(Feet)	(Days)	(Inches)
1	30	104	1.07
2	30	104	3.20
3	30	104	8.32
4	30	84	6.70
5	30	84	5.96
6	25	84	7.78
7	25	84	0.96
8	20	84	0.78
9	30	84	7.5
10	30	84	10.13
11	25	84	3.11
12	25	84	2.64
13	20	84	0.6

To maintain conservatism while comparing actual settlement data to the predicted settlements, the data collected was not used to re-estimate the maximum (worst case) total settlement, but rather to estimate a coefficient of consolidation, c_v, and compute a new rate of settlement. Those values were then used to estimate the total and remaining settlement at each of the individual monitoring points

In order to estimate c_v, the maximum settlement measured—10.13 inches at Monitoring Point # 10 after three months—was compared to the maximum (worst case) predicted settlement of 26 inches after 24 – 48 months. This was reasonable in that the worst case predicted settlement assumed a 30-foot thick cohesive layer and Monitoring Point #10 fell within the western section of the site. Although the worst case predicted settlement also assumed 9 feet of fill, which was probably not accurate for the location of monitoring Point #10 considering the very variable surcharge height, the comparison was used to estimate c_v, which is independent of the amount of loading.

Figure 2 – Settlement vs. Time (Monitoring Points # 1 - #13)



Using the following equations from Terzaghi (1943) a simulated time vs. settlement curve was produced similar to those shown in Figure 2.

$$T_v = \frac{c_v}{H^2} t \qquad (1)$$

$$T_v = \frac{\pi}{4}\left(\frac{U\%}{100}\right)^2 \qquad \textit{For values of U\% between 0 and 52.6} \qquad (2)$$

$$T_v = 1.781 - 0.933 \log_{10}(100 - U\%) \qquad \textit{For Values of U\% greater than 52.6} \qquad (3)$$

where,

T_v = *Time Factor*

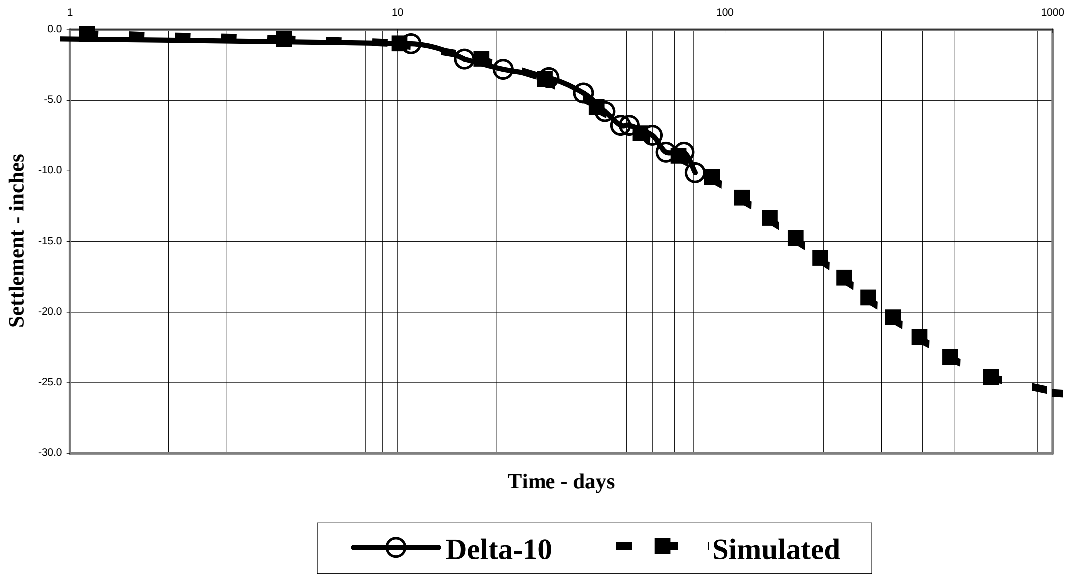
H = *max distance for water to travel = ½ thickness of cohesive layer*

$U\%$ = *Degree of Consolidation*

Using an iterative process and keeping the maximum settlement constant at 26 inches, the value of c_v was altered until the shape of the simulated time vs.

settlement curve matched (as closely as possible) the settlement curve based on Monitoring Point #10 (See Figure 3). The value of c_v for this curve was 0.392 ft^2/day, approximately 1.8 times the c_v value estimated based on the laboratory test results and used in the initial settlement calculations.

Figure No. 3 – Settlement vs. Time (Monitoring Point #10 and Simulated Plot)



Using this value for c_v and the cohesive layer thicknesses shown on Table No 2, the maximum estimated settlements were revised/estimated at each of the individual monitoring points, matching the measured curves to the extent possible. Table No. 3 shows the total estimated and remaining settlements at each of the individual monitoring points. (The table is sorted in descending order based on the amount of remaining settlement.)

Table No. 3 – Total Estimated and Remaining Settlement at Monitoring Points
(w/ c_v = 0.392 ft^2/day)

Mon. Point	Current Measured Settlement	Estimated Thickness of Cohesive Layer	Estimated Percent Consolidation	Total Estimated Settlement	Total Remaining Settlement
	(Inches)	(Feet)	(%)	(Inches)	(Inches)
10	10.13	30	38.9	26.0	15.9
9	7.50	30	37.5	20.0	12.5
4	6.70	30	37.2	18.0	11.3
3	8.32	30	43.8	19.0	10.7
5	5.96	30	36.1	16.5	10.5
6	7.78	25	43.2	18.0	10.2
2	3.20	30	42.7	7.5	4.3
11	3.11	25	47.8	6.5	3.4

12	2.64	25	44	6.0	3.4
7	0.96	25	38.4	2.5	1.5
1	1.07	30	42.8	2.5	1.4
8	0.78	20	63.9	2.0	1.2
13	0.60	20	40	1.5	1.0

Based on the same c_v, the time for 90% of the total settlement to occur was estimated at 510 days within the western-most section (30-foot thick cohesive layer), 360 days within the middle of the site (25-foot thick cohesive layer), and 240 days within the eastern-most section. Table 4 shows the averages from within each section of the site—based on all of the monitoring points within the respective sections.

Table No. 4 – Average Estimated Remaining Settlement

Portion of Site	Average Measured Settlement	Average Estimated Remaining Settlement	Estimated Remaining Time to 90% Consolidation
	(Inches)	(Inches)	(Days)
Western Section	6.13	9.5	416
Middle Section	3.63	4.6	266
Eastern Section	0.69	1.1	146

Based on the average remaining settlements and the estimated remaining time (based on the current conditions) for those settlements to occur, the following decisions were made with regard to controlling post-construction settlement within the parking area:

- Due to scheduling restrictions and the amount of time that would be required to remove any surcharge and begin final grading, it was estimated that any surcharge/wick drain period could only be maintained for 3 – 4 months.

- The site was divided into three sections—based on thickness of cohesive layer—and the use of wick drains and/or surcharge within in section was evaluated.

- Eastern Section – With only 1 – 2 inches of remaining settlement anticipated and only 5 months for most of that settlement to be completed, the use of wick drains and/or surcharge would not provide any additional benefit. In fact, with this being only in the parking lot, settlements on the order of 1 – 2 inches would be acceptable. As such, the use of wick drains or surcharge within this section was eliminated.

- Middle Section – With 4 – 5 inches of remaining settlement anticipated and with most of that expected to occur within the next 7 - 9 months, the use of wick drains would not provide much additional benefit. In fact, of the four monitoring points in this section, only Point #6 had estimated remaining settlement higher than the average. Considering that much of the remaining settlement would occur during the next few months, before final removal of the excess fill and construction of the parking lot began, post-construction settlement within this section would likely be within tolerable limits. As such, the use of wick drains was eliminated, however, a surcharge height equal to at least six feet above final grades was maintained for the next 3 – 4 months.

- Western Section – The average remaining settlement within this section of the site—9 – 10 inches—along with the expected 13 – 14 month timeframe for most of it to occur, required preventative measures. Only Monitoring Points #1 and #2, which were very near the platform area, were below 10 inches of expected remaining settlement. Considering the 3 – 4 month schedule before final removal of the surcharge and construction of the parking lot would have to begin, the use of wick drains within this section was unavoidable.

Assuming that installation of wick drains would require at least one month, the original, wick drain design-spacing was revised based on the expected remaining settlement. For consistency, the revised analysis maintained the following items as they were within the original spacing design calculations:

- diameter of the wick drains, d, was equal to 2.58 inches
- triangular layout of the wick drains
- $c_h = c_v$
- target percent consolidation set at around 85%

Based on charts and equations from Hansbo (1979), if the wick drains were installed at the original 5-foot spacing, 98% of primary consolidation could be completed within the 3 months after wick drain installation. However, if a 7-foot spacing were to be used, it would not only result in a cost savings, but it would also allow wick drain installation to be completed earlier. Estimates based on Hansbo, showed that with a 7-foot spacing, up to 86% of primary consolidation could be completed within the same 3-month span. Since this was not only similar to the 85% targeted by the original design calculations, but also resulted in a cost savings, the 7-foot spacing was adopted.

SETTLEMENT CONTROL WITHIN THE PLATFORM AREAS

It was realized early on that constructing 5 feet (or more) of surcharge within either of the platform areas, and installing wick drains within the northbound platform (across the tracks from the parking area) would not be possible, based on the operational restrictions of the existing freight track. The use of piles to support the platforms was still not an option because of the pre-cast station platform panel designs.

From a constructibility standpoint, the use of a low density fill was a much more practical alternative to eliminate the increase in net loading due to the several feet of fill and the station platform structures. However, the major pitfall to using a low-density material was the groundwater elevation at the site, which was approximately 6 feet below the surface within the platform areas and would limit the thickness of the low-density fill.

The initial assessment of alternatives used a typical unit weight of 40 pcf for a low-density fill. With that unit weight the estimated depth of in-situ material to be removed and replaced with a low-density fill would have been greater than the groundwater depth of six feet. As such, it was uncertain if the use of low-density fill could be used based on both placement and buoyancy concerns.

Continued review of options continued to lead back to the use of low-density fill as the most suitable construction alternative. New calculations showed that a load balance could be achieved with only 4 – 5 feet of excavation, if material were used with an average unit weight in the range of 30 – 33 pcf. These extremely low unit weights were though to be able to be achieved by increasing the amount of entrained air in the fluid material.

After numerous discussions with low-density cellular concrete fill (LDCCF) suppliers and several test pours, there was confidence that the average unit weight of 30 pcf could be achieved. The test pours showed that although the 30 pcf could be achieved at the discharge of the truck, both pumping the concrete to the placement point and/or high drop-heights usually increased the final unit weight. The test pours also showed that single full height (5-foot) pours sometimes resulted in a ‘collapsing’ effect, probably due to an imbalance in the curing rates.

These placement considerations were easily overcome at the southbound platform, which was accessible by the concrete trucks. Longer chutes were used to reduce the drop height. The northbound platform, however, was across the active freight tracks from the parking area and therefore not accessible by the concrete trucks. For that platform, a system of extra long wooden chutes were devised that were mounted on a rail cart enabling the chutes to be moved along the platform excavation. A detailed concrete placement plan was also developed that allowed the placement of the low-density material within a limited track outage period and meeting the stringent quality control and monitoring provisions for the use of the material

Conclusions and Some Measurements

By taking advantage of the stockpiling (uncontrolled surcharge) and using unique settlement control techniques within individual areas of the site, allowed the project to meet the tight construction schedule. A total of four different methods were used to control post-construction settlement at the Route 73 station and parking lot. Each of the methods proved not only to be successful, but also probably the most efficient within the respective section.

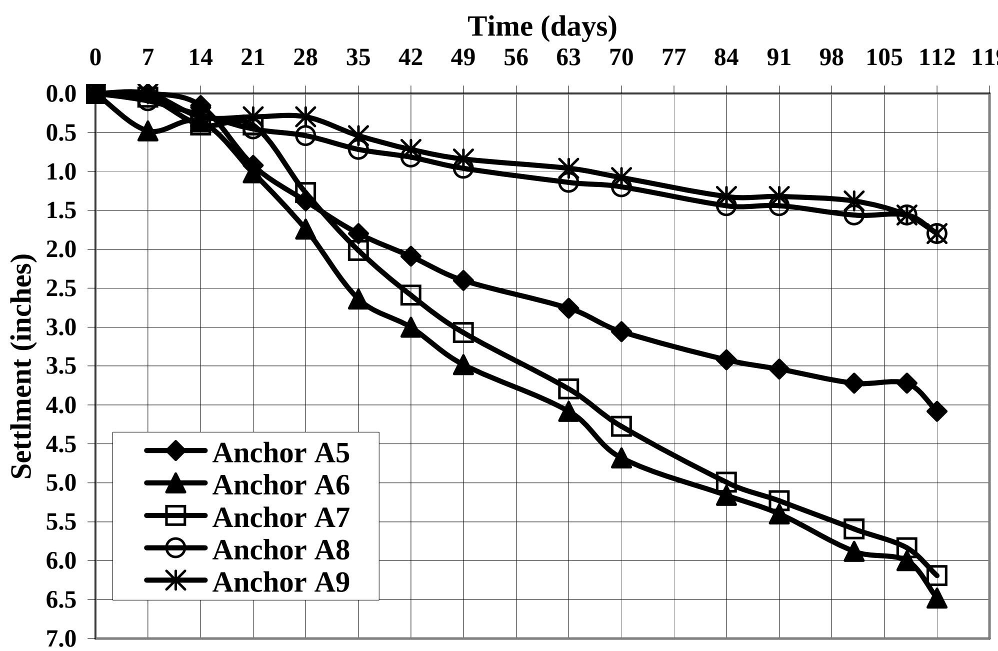
Platform Area – a load balance was achieved by replacing in-situ material with a low-density cellular concrete fill (LDCCF). The average movement measured at the platform locations, after placement of the LDCCF was on the order of a third of an inch, with the worst case being just under a half an inch. Some of this movement may also have been attributed to minor shrinkage of the concrete as it continued to cure and not necessarily to settlement of the underlying soils. The total movement maintained the platforms within the tolerance.

Eastern Section of Parking Lot – surcharging was used to obtain at least 40% of the expected settlements (on the order of 1 inch) prior to start of final construction of the parking lot. Most of this settlement was completed during the uncontrolled surcharging phase. This area did continue to have some surcharge during the controlled surcharging phase, but with only one inch of additional settlement expected, the use of wick drains and controlled surcharge was eliminated and no further monitoring was performed.

Middle Section of Parking Lot – surcharging was used to obtain an average of 60 – 70% of the total expected settlement (on the order of 5.5 inches) prior to start of final construction of the parking lot. Approximately 45% of the total expected settlement occurred during the uncontrolled surcharging phase. With only 4 – 5 inches of additional settlement expected, the use of wick drains was eliminated, but a controlled surcharge resulted in an additional amount of settlement just under 2 inches over the three month stretch (See settlement plots for Anchors A8 and A9 on Figure 4).

Figure No. 4 – Settlement vs. Time

(Anchors A5 – A9 during controlled surcharge and wick drain phase)



Western Section of Parking Lot – wick drains and surcharge were used to obtain an average of 70 – 80% of the total expected settlement (on the order of 12 inches). Approximately 40% of the total settlement occurred during the uncontrolled surcharging phase. Controlled surcharge along with wick drains were used to obtain an additional 4 – 6.5 inches of settlement (See settlement plots of Anchors A5, A6, and A7 on Figure 4). Wick drains were installed within the area of A6 on or before day 7 of settlement monitoring and within the areas of A5 and A7 before day 14 of monitoring.

References

1 – Terzaghi, Karl, Theoretical Soil Mechanics, John Wiley and Sons, Inc., 1943

2 – Hansbo, S., "Consolidation of Clay by Band-Shaped Prefabricated Drains", Ground Engineering, 1979.