BUILDING THE DEVIL'S PLAYGROUND:
How a Ground Improvement Program Eliminated the Need for Pile Foundations

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The dream to bring New Jersey Devils hockey to the largest city in New Jersey became a reality in the summer of 2005, when construction began for the Prudential Center in downtown Newark. The Prudential Center site encompasses an entire city block that had a varied history of uses ranging from a cemetery in the late 18th century, to a rail yard and train station for the now-defunct Central Jersey Rail Road in the 19th and early 20th centuries, to commercial development in the latter half of the 20th century. Each of these prior uses presented challenges to the design and construction of the Prudential Center that required innovative engineering solutions, including: archaeological investigation and exhumation of the former cemetery occupants, protection of historic buildings surrounding the site, and extensive demolition to remove old train bridge foundations.

The design team was required to develop potential foundation systems for the arena. Several foundation concepts were evaluated for cost and constructability, including: driven piles, drilled shafts, and shallow foundations on improved subgrade. Following a detailed cost analysis and value engineering exercise, the decision was made to support the arena on spread footings following the completion of a multi-phased ground improvement program consisting of a combination of dynamic compaction and removal and replacement. To evaluate achievable allowable bearing pressure as part of the design, a dynamic compaction test section was performed within the building footprint prior to the start of production work; this resulted in an increase of the allowable design bearing pressure from 2 tons per square foot (tsf) to 3 tsf. This reduced the expected foundation costs by 30% and gained sufficient time in the schedule to allow for the completion of the arena in time for the New Jersey Devils 2007-2008 hockey season.

BACKGROUND

The dream to bring New Jersey Devils hockey to the largest city in New Jersey became a reality in the summer of 2005, when construction began for the Prudential Center in downtown Newark. After several years of negotiating between the City of Newark, local landowners, area developers, and the Devils themselves, a deal was finally struck to erect Newark Arena, now known as the Prudential Center, right next to City Hall. This is not to say, however, that once the site location was finalized, that no further challenges were encountered in the construction of Newark's new crown jewel.

Site History

The Prudential Center site encompasses an entire city block and had a varied history of uses ranging from a cemetery in the late 18th century, to a rail yard and train station for the now-defunct Central Jersey Rail Road in the 19th and early 20th centuries, to a commercial development in the latter half of the 20th century.

The site is located in Newark, New Jersey, and is generally bounded by Edison Place to the north, Broad Street to the west, Lafayette Street to the south, and Mulberry Street to the east. An aerial layout of the site prior to construction is shown in Figure 1.

Prior to construction of the Prudential Center, most of the interior of the site was occupied by asphalt-paved, at-grade parking lots. The former Renaissance Mall along Broad Street had recently been demolished, and several other abandoned buildings existed around the perimeter of the site. Additionally, the alignment of Lafayette Street formerly existed across the southern end of the site; the street was relocated prior to arena construction. The façade of the former Renaissance Mall, a six-story office building and the First Presbyterian Church existed directly adjacent to the site along Broad Street, and were not within the proposed arena footprint.

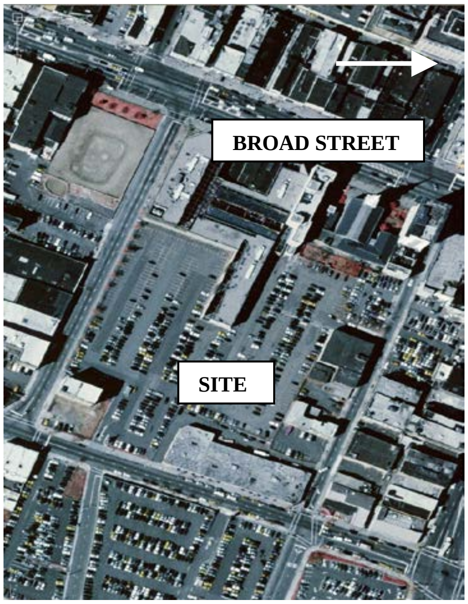

Figure 1 – Pre-Construction Aerial of Arena Site

As part of the data gathering process for the project, a review of historical documents indicated that the northern portion of the existing parking lot was used as a cemetery until the late 1950's. Although it was reported that all marked graves within this cemetery were disinterred around 1959, the geotechnical investigation for the arena project unearthed several historical artifacts, including headstones dating to the 1700's and several sets of human skeletal remains.

Available Sanborn maps also indicated that the southern portion of the site was once used as a rail yard for Central Railroad of New Jersey, with rails running in the east-west direction across the site. Evidence of the former railways, primarily in the form of concrete grade beams, was uncovered during excavation for the demolition of the former Renaissance Mall. A Sanborn map of the site from prior to the 1950's is shown in Figure 2.

Immediately prior to construction, the site was relatively level, with existing grades within the proposed arena footprint sloping gently downward to the east, with elevations ranging from approximately elevation 37 feet at the façade of the Renaissance Mall in the southwestern corner of the site to approximately elevation 26 feet along Mulberry Street on the eastern portion of the site.

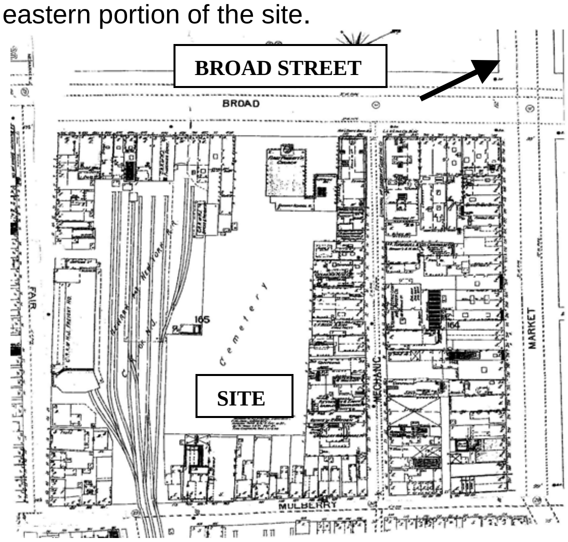

Figure 2 – 1950's Sanborn Map of Arena Site

Proposed Arena Construction

As it stands today, the Prudential Center encompasses a footprint of approximately 340,000 square feet. Subsequent to construction of the main arena and the completed relocation of Lafayette Street, a practice ice rink facility was constructed immediately adjacent to the arena to the south.

The first finished floor elevation of the arena slab exists at about elevation 35.33 feet; this required fills on the order of 5 feet and cuts of up to 3 feet from the pre-construction grades. No below-grade levels were incorporated into the arena construction. The main slab underlying the arena floor was constructed as slab-on-grade, with refrigeration piping for the ice surface incorporated into the slab design.

Based on information provided by the structural engineer during the final design phase, column dead plus live loads for the arena were to range from 60 kips to over 2,100 kips within the arena; with the more significant loads existing in the four corners of the arena, where the long roof spans were designed to concentrate the loading conditions in these areas into "super columns".

DESIGN PHASE

Given the scope and complexity of the construction of such a significant structure in a relatively tight urban setting, the design period for the arena included several different phases, in an attempt to arrive at a cost-effective and schedule-appropriate foundation solution.

Investigation

In the several years that it took the City of Newark to finalize a location for the arena, several different subsurface conditions were conducted by the Geotechnical Engineer, Langan Engineering and Environmental Services (Langan). Initially, a preliminary investigation consisting of 14 borings was completed in August of 1999 for the then contemplated "Newark Sports and Entertainment Village" site to the east of the present-day Prudential Center location. Four of these borings were advanced within the vicinity of the existing arena footprint and were incorporated into the final foundation design.

In July and August 2004, a second investigation consisting of 28 borings and 11 test pits was conducted at the current site. Four of the borings were converted to groundwater monitoring wells upon completion. All 11 test pits were excavated within the existing arena footprint.

A third investigation, consisting of three borings advanced at accessible corner locations of the arena footprint, in the proposed super column locations, was completed in March 2005 during the design development phase of the project.

Regional Geology

The site lies in the Newark Basin of the Piedmont Physiographic Province. Soils in the vicinity of the site generally consist of sand and silt intermixed with some clay and gravel-sized particles and occasional cobbles and boulders. Lenses and localized pockets of silt are typically encountered throughout the stratum. The underlying bedrock formation consists of reddish-brown to brownish-purple siltstone and shale and is identified as part of the Passaic Formation on the Bedrock Geologic Map of Northern New Jersey. The site lies in an area of relatively low seismic concern.

Subsurface Conditions

Data obtained during the various subsurface investigations conducted for the project indicated that the subsurface conditions underlying the arena site generally consisted of miscellaneous fill material, underlain by glacial outwash sands, glacial till, and shale bedrock. Groundwater was encountered at depths ranging from 9 to 28 feet below the existing site grades.

A brief description of each material encountered during the investigation phase of the project is provided below; see Figure 3 for a generalized soil profile:

<u>Miscellaneous Fill</u> – A layer of miscellaneous fill up to about 15 feet thick was encountered across the entire site. The miscellaneous fill material generally consisted of coarse to fine sand with some silt and varying amounts of gravel, cobbles, and debris, including concrete, brick, plastic, glass, and rubber. SPT N-values within the fill material range from the weight of the hammer advancing the split-spoon sampler to 100 blows over 2 inches, and averaged approximately 22 blows per foot (bl/ft). During the test pit excavations, the remnants of a below grade concrete walls, slabs, gravestones, and skeletal remains were encountered.

<u>Sand</u> – A layer of glacial outwash sands was encountered underlying the fill layer, and ranged in thickness from approximately 17 to 44 feet. Generally, the sand layer consisted of medium dense to dense, poorly graded, medium to fine sands, with varying amounts of coarse sand, fine gravel, and silt. Relatively thin, isolated pockets of silt were encountered sporadically throughout the sand layer. SPT N-values within the sand layer range from 7 bl/ft to 118 bl/ft, and average approximately 26 bl/ft. The lower N-values generally occurred immediately below the water table; overall, however, the N-values within the sand layer tended to increase with depth.

<u>Glacial Till</u> – A layer of glacial till was encountered underlying the sand layer, and ranged in thickness from approximately 3 to 24 feet. The glacial till layer generally consisted of very stiff to hard silts and medium dense to dense sands, with varying amounts of gravel, cobbles, and boulders. SPT N-values in the glacial till layer ranged from 15 bl/ft to 100 blows

over 2 inches, and averaged 59 bl/ft. It is likely that the higher N-values were the result of cobbles and boulders buried within the glacial till layer.

Shale Bedrock – The overburden soils are then underlain by shale bedrock, the top of which was encountered at depths ranging from approximately 35 to 65 feet below existing grade (elevation -4 to -35 feet). The elevation of the top of rock generally decreases moving east across the site, towards Mulberry Street. The general quality of the rock varied, and in almost every instance, the upper portion of the rock (generally 5 feet on average) was found to be decomposed in nature.

Groundwater – Groundwater was encountered at depths ranging from 9 to 28 feet. These depths correspond to a range from elevation 5 feet to elevation 21 feet. Groundwater was observed to stabilize within the monitoring wells at depths of 18.5 to over 25 feet, corresponding to elevations between about 12.5 to 5 feet. It is likely that the groundwater encountered at shallower depths was perched on buried obstructions within the fill layer.

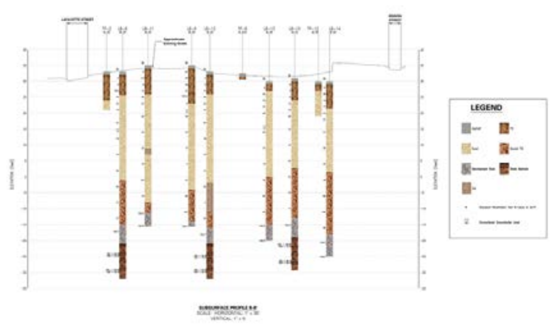

Figure 3 – Generalized Soil Profile

Obstacles to Overcome

Based on the conditions encountered during the subsurface investigation, there were two main geotechnical concerns related to the foundation design for the proposed arena. First, a relatively thick layer of uncontrolled fill material was found to exist across the entire footprint. The nature and relative density of the fill material was found highly variable, primarily because the fill was placed without any engineering controls. Additionally, significant buried obstructions were encountered within the fill due to demolition of previous structures on-site. As such, the fill layer in its encountered state would have been unsuitable to provide foundation support for the proposed structures without improvement.

Secondly, pockets of loose to medium dense sand with relatively low foundation bearing capacity were encountered directly underlying the miscellaneous fill layer.

In addition to the challenges presented foundation design by the encountered soils, constructability issues based on the results of the archaeological investigation, the protection of historic buildings surrounding the site, and extensive demolition efforts to remove old train bridge foundations had to be overcome.

Foundation Options

Based on the subsequent engineering evaluation, two main foundation solutions were deemed suitable. One alternative was to implement a ground improvement program to allow for shallow foundations and slab-on-grade construction. The second alternative was a deep foundation solution with a structural floor slab. A discussion of each option is provided below.

Shallow Foundations with Ground Improvement

Two main types of ground improvement were considered for the project. First, the fill material and underlying loose sands could be improved by implementing a dynamic compaction program. Alternatively, the fill material could be removed and replaced as structural fill material, once the underlying sand material was compacted. The main intent of either option was to allow for conventional shallow foundation and slab-on-grade construction, which is almost always a more economical approach than deep foundation systems.

It should be noted, that each option had some drawbacks that needed to be addressed during the evaluation process. Specifically:

> *Dynamic Compaction Option* – In an urban setting such as the arena site, the biggest issue associated with dynamic compaction is minimizing vibrations on adjacent structures. Typically used methods to limit vibrations at adjacent structures generally include the

excavation of seismic cut-off trenches, installation of sheeting, adjusting the dynamic compaction program, or performing limited removal and replacement when in very close proximity to sensitive structures. Also, vibration monitoring would be performed during all dynamic compaction work for the arena project. Based on these considerations, the premium associated with the dynamic compaction option was estimated to be about $1,300,000.

Removal and Replacement Option –The removal and replacement option was to consist of the removal of all fill material to the top of the natural sand, heavy surface compaction of the loose sands, and replacing the excavated material as structural fill. It was expected that the depth of fill removal would extend up to 12 feet and would average about eight feet throughout the site. During removal of the fill, unsuitable material encountered would have to be separated out and properly disposed of off-site. Prior to replacing the fill material, the exposed subgrade would be surface compacted and any soft or deleterious materials would be removed and replaced with select granular fill material. While significant amounts of investigation were performed at the site, the biggest concern with respect to the removal and replacement option was the possibility that unknown environmental concerns existed given the urban nature of the site. Additionally, there was concern that large quantities of debris would be encountered, making the fill material unsuitable for reuse. A budgetary premium for the removal and replacement option was estimated to be about $1,900,000. However, it is important to note that this estimate assumed the reuse of all excavated soils and limited import, and did not account for unknown environmental conditions. This could have had a serious impact on the cost of this option.

Pile Foundations and Structural Floor Slabs

As an alternative to the shallow foundation option, pile foundations and structural floor slabs were also considered. It was anticipated that steel pipe piles or H-piles could be driven to bedrock to achieve allowable capacities ranging from 100 to 150 tons. Pile lengths were expected to range from approximately 35 to 65 feet across the site. A budgetary installation for pile installation was estimated to be about $2,200,000; however, this number did not include the additional premium that would be incurred by constructing a structural floor slab system.

Selected Solution

Based on detailed constructability reviews, cost estimates, and feasibility discussions, it was decided that a hybrid ground improvement program and conventional shallow foundations with slab-on-grade construction would be the more economical option for the project. Specifically, the ground improvement program to be implemented was to consist of a combination of dynamic compaction and removal and replacement. Dynamic compaction would be implemented throughout the majority of the site; the removal and replacement would be implemented around the site perimeter to minimize the effect of off-site vibrations on adjacent structures. Details of the recommended ground improvement measures are as follows:

Dynamic Compaction – The recommended dynamic compaction program was to consist of dropping a 15-ton weight from a height of 55 feet at selected locations over the entire building footprint. The height and weight chosen for the program was based on the empirical correlation for anticipated depth of improvement as follows:

$$D = n\sqrt{WH} \qquad (1)$$

where: D = depth of influence (m)
n = empirical coefficient
W = weight of tamper (Mg)
H = drop height (m)

The program implemented was a three-pass system. The first pass consisted of dropping the weight at least four times at each location on a 10-foot by 10-foot grid across the site. The second pass consisted of the same, with the grid pattern offset from the first pass by five feet in each direction. In both passes, the grid covered the entire arena footprint plus 20 feet beyond the building line in loading dock areas, and 10 feet beyond the building limit elsewhere. The third pass then consisted of four additional drop points which blanketed each footing area, and one additional drop point every six feet along thin strip footings. Upon completion of the three passes, the upper few feet of soil was loose from grading of the crater formations. To remedy this, surface compaction consisting of at least six passes of a 10-ton vibratory roller was completed.

In order to assist with minimizing vibration damage to off-site structures, staging of the dynamic compaction program was completed in a manner which started furthest from critical structures and slowly progressed towards them. This manner of proceeding allowed for an understanding of how vibration levels increased as the dynamic compaction work got closer to structures. Protective measures, such as isolation trenches or adjusting the height of the drops, were then implemented, as required, as the work approached sensitive structures.

<u>Removal and Replacement</u> – Although the purpose of isolation trenches and reduced height of drops during the dynamic compaction process can reduce vibration levels, structures within 100 feet of the operation were still a concern. In these areas, the fill material was removed to the top of the glacial outwash sands, the exposed surface was compacted with several passes of a 10-ton smooth-drum vibratory roller, and then replaced as structural fill, once wood, metal, rubber, other deleterious materials and larger debris was removed.

Foundation Design Criteria

Following the ground improvement program discussed above, footings for the project were preliminarily designed using an allowable bearing capacity of two tsf. However, given the experience of the design team, it was thought that a higher design bearing pressure could be achieved; to evaluate this, a test section was completed at the onset of construction. Pending the results of the test section, allowable bearing capacities of up to three tsf were thought possible. Significant savings were to be realized in foundation construction costs if the allowable bearing capacity could be increased.

Based upon settlement criteria provided by the structural engineer, the anticipated allowable total settlement for the arena was two inches. Allowable differential settlement between adjacent columns was ¾-inch. Given the granular nature of the soils which existed beneath the arena site, it was expected that the majority of any settlement would occur during the construction process.

CONSTRUCTION PHASE

Following the completion of nearly two years of design and evaluation work, construction of the arena was set to begin in 2005.

Dynamic Compaction Test Section

As mentioned above, a dynamic test section was completed by the specialty geotechnical contractor, Densification, Inc., at the onset of the construction phase with two main goals:

- Evaluate whether an achievable allowable bearing pressure of three tsf could be achieved following the implementation of the dynamic compaction program, and;
- Evaluate vibration levels to be anticipated during production work so that the appropriate protection measures might be implemented ahead of time.

<u>Test Section Details</u>

The test section implemented was approximately 50 feet square in plan area, and was located in the southeastern corner of the arena, at one of the super column locations and in the location of the worst soil conditions. The test section consisted of a 15-ton weight being dropped from a height of 55 feet, over a three pass system, as previously described. It was important to mimic the program which was to be carried out during the production work. A photo of the test section work in progress is shown in Figure 4.

<u>Subsurface Investigation</u>

Both before and after completion of the test section, additional subsurface investigation consisting of soil borings and cone penetrometer testing (CPTs) was conducted by Langan. A total of four soil borings and five CPTs were advanced prior to the test section work. Two weeks following the completion of the test section work, the same tests were replicated in close proximity to the pre-improvement testing locations. All borings were sampled continuously to a depth of 27 feet below the existing site grades; the CPT probes were all advanced to 30 feet below the existing site grades.

Figure 4 – Photo of Test Section Work

Vibration Monitoring

Another important aspect of the test section was the evaluation of vibration levels during the dynamic compaction work. During the execution of the test section pounding, vibration monitoring was performed so that a site-specific vibration attenuation curve could be developed. In conjunction with the test section, two different methods for limiting vibrations were evaluated. Along one side of the test section, a seismic cut-off trench was excavated. Along another side of the test section, a 25-foot deep steel-sheet pile wall was installed. Vibration levels were monitored both sides of the trench and sheet pile wall, at various distances from the drop locations, so that an assessment as to the effectiveness of each option could be made.

Results

Based on the post-improvement testing, reasonable improvement was observed in the upper 18 to 25 feet of soil. Specifically, the following observations were made:

- Average SPT N-values within the upper 25 feet increased from 26 bl/ft to 29 bl/ft, but most importantly, the minimum N-values observed increased from 7 bl/ft to 14 bl/ft. A figure showing the pre- and post-improvement averages is shown in Figure 5.
- Average CPT tip resistance values within the upper 30 feet increased from 113 tsf to 129 tsf. A figure showing the pre- and post-improvement averages is shown in Figure 6.

Additionally, based on the full-time observation of the test section work, uniform conditions were noted in terms of crater depth and ground response, which is very positive in terms of the anticipated overall effectiveness of the program. Based on the information collected, and a detailed settlement analysis which incorporated several different analytical methods, the recommendation was made to move forward with a design allowable bearing pressure of 3 tsf.

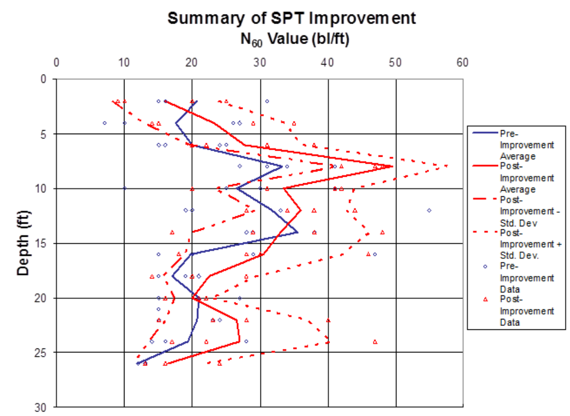

Figure 5 – SPT N-value Comparison

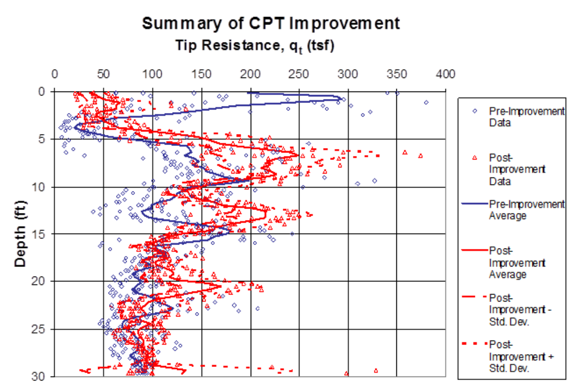

Figure 6 – CPT Tip Resistance Comparison

A plot showing the vibration levels both in front and behind the sheet pile wall and seismic cut-off trench are shown in Figure 7. Overall, the cut-off trench was observed to be more effective than the steel sheet pile wall at reducing vibration levels during the dynamic compaction work. Specifically, vibration levels were reduced by the cut-off trench and sheet pile wall 70% and 35%, respectively. As a result, the recommendation was made to move forward with seismic cut-off trenches adjacent to sensitive structures, with maximum vibration levels at various elements being recommended as follows:

- 1.0 in/sec near utilities;
- 0.5 in/sec near most structures;
- 0.25 in/sec near the church.

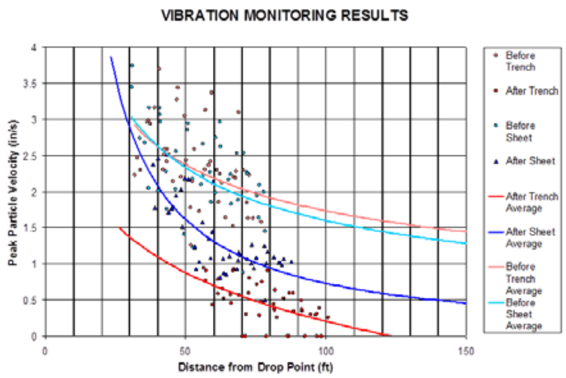

Figure 7 – Vibration Monitoring Data

<u>CONSTRUCTION PHASE</u>

Once the dynamic compaction test section was successfully completed, foundation construction was clear to begin. Given the history of the site, however, there were several challenges that still needed to be addressed prior to foundation construction.

<u>Additional Site Preparation Challenges</u>

As mentioned above, portions of the site, primarily around the perimeter, were occupied with multi-story structures prior to construction. These structures, along with any below-grade levels and foundations had to be demolished and removed prior to foundation construction. Following demolition, these excavations were backfilled with structural fill as the first part of the ground improvement program. In addition to the existing structures, several below-grade structures associated with the former rail yard on site needed to be identified and removed. A photo showing a typical rail foundation that was encountered is shown in Figure 8.

Parallel to the demolition activities at the site, the fact that human remains were encountered during the investigation process needed to be addressed prior to any earthwork activities at the site. In order to identify and remove any remains from the site, an archaeological excavation of the former cemetery was conducted prior to the dynamic compaction phase. Completed in a period of about four months, a team of up to 60 archeologists removed on the order of 2,100 sets of human remains that dated back to the 1600's. The remains were identified, located, and taken to a funeral home for cremation; all ashes from the project were then returned to a monument in the yard of the adjacent church. A photo illustrating the on-site archaeological dig is shown in Figure 9.

Figure 8 – Typical Rail Foundations

Figure 9 – Archaeological Excavation

Dynamic Compaction Production Phase

Once the archaeological excavation, demolition, and test section work were completed, the dynamic compaction production work was completed. Production work was completed in an identical manner to the test section, and observed continuously to evaluate crater depths, vibration levels, and overall ground response. Charting of the crater depths during the production phase became very important during the completion of the borings advanced to evaluate the effectiveness of the dynamic compaction program. Specifically, one area of the site demonstrated N-values which were below the minimum stated acceptance criteria of 20 bl/ft. By reviewing the crater depth information collected during the program, the area which needed to be re-pounded was easily identified and additional drops were successfully carried out. A photo taken during the production phase is shown in Figure 10.

Figure 10 – Dynamic Compaction Production

Overall, the results of the post-production testing were even more favorable than those obtained following the test section work. Specifically, an average N-value of 31 bl/ft was obtained across the site. A plot illustrating the average SPT N-values prior to construction, following the test section, and following the production work is shown in Figure 11.

Foundation Construction

Following the extensive ground improvement program at the site, foundation construction moved forward as planned, with the biggest obstacle to overcome being the winter weather conditions. Given the size of some of the arena foundations, several days were required in some instances to erect the forms and place rebar prior to concrete placement. The bitterly cold weather at the time of much of this work exposed the improved footing subgrades to extensive frost risk. To combat this, when freezing weather was anticipated, forms were wrapped in concrete blankets the night prior to a concrete pour, and propane heaters were placed within the forms to elevate the temperature to the point where the foundation concrete was not placed on frozen subgrade. A photo taken during the foundation construction phase is shown in Figure 12.

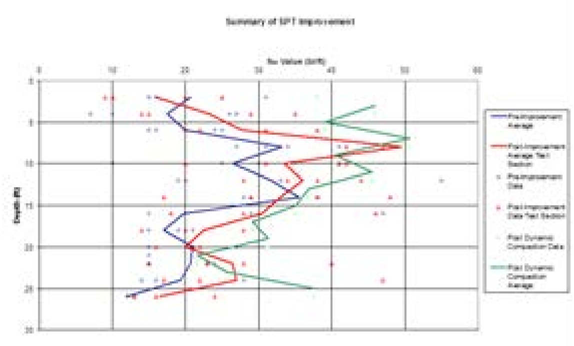

Figure 11 – Post-Production Results

Figure 12 – Foundation Construction

CONCLUSIONS

Complex projects such as these always have lessons learned, and always draw from the engineering and construction experience of the design and construction team. Given the extremely tight window which was in place to complete construction of the arena, no room for error existed when it came to the schedule. To be able to provide relief to the schedule, where possible, was all the better. By successfully implementing a thorough subsurface investigation and dynamic compaction test section, critical activities which needed to be completed to avoid delays were anticipated and accounted for in the schedule. The lessons learned and conclusions derived from this project, in no particular order, are as follows:

- Thorough geotechnical investigations in can be critical to uncovering potential project issues, particularly in urban settings. Had the investigation for this project not uncovered the archaeological impacts to the site, the schedule for the project would have been in serious trouble.

- Conducting a test section may seem like an extra step that can take time, but in the case of the arena, the overall concrete for the foundations was reduced by 30% by achieving an allowable bearing pressure of 3 tsf; this also had a positive impact on the construction schedule and was a real triumph for the value engineering process.

- Understanding the vibration levels associated with a dynamic compaction project as soon as possible is critical to avoiding damage to nearby structures, particularly in urban settings.

- Seismic cut-off trenches are generally more effective than sheet-pile walls in reducing construction-induced vibrations.

- Ground improvement programs, where applicable, can offer a viable and economical alternative to deep foundations.

ACKNOWLEDGMENTS

The authors would like to extend their appreciation to the New Jersey Devils, as well as the entire construction team, for their dedication and involvement in this project. The owner's willingness to trust the judgment of their consultants led to a successful project completion and a practical, optimized design. Also to be noted is the significant input of the Structural Engineer, Thornton Tomasetti, whose ability to think "outside the box" allowed the project to move along the successful path that was chosen.

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