Mar 8th, 12:00 AM

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CASE HISTORY OF TWO BUILDINGS EXPERIENCING LARGE POST CONSTRUCTION SETTLEMENTS

WILMINGTON, DELAWARE

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ABSTRACT

This paper discusses a case history involving two buildings which were constructed over compressible soils at a site along the Christina River in Wilmington, Delaware. The buildings, which were constructed in 1987, have undergone significant settlement of both shallow and deep foundation elements. As of early 1995, some of the pile foundations for one of the buildings were observed to have settled as much as 8 inches, while portions of the floor slab were observed to have settled as much as 9-1/2 inches since the completion of construction. As a result of these large settlements, the owner retained the author's firm to evaluate site soil and structural conditions and provide recommendations for remedial action.

This paper presents a summary of the soil conditions, the settlements which occurred after construction, as well as the remedial measures taken to repair the structure.

KEYWORDS

Settlement; differential settlement; compressible soils; pile settlement

INTRODUCTION

In 1986, the owner of a facility in the City of Wilmington, Delaware needed to relocate their retail store and workshop facility. The owner had limited time to vacate an existing facility and find another location to maintain their operations. Two of the buildings constructed at the new facility location are the subject of this paper.

An architect was retained by the owner in 1986 to design the new facility and subsequently, retained a structural engineer to design the foundations and buildings. As part of the building foundation design, the project design professionals retained a drilling contractor to perform eight Standard Penetration Test (SPT) borings at the site.

The design team did not retain a geotechnical engineer to assist with the design of the structure. As a result, no laboratory testing of the soils from the original test borings was performed to determine engineering properties for the design of the new buildings.

The Structures

The two buildings which are illustrated in Figure 1, consist of a store area (Building A) and a shop area (Building B), which are connected by a roofed enclosure.

The store area is approximately 19,000 square feet, while the shop area is 36,000 square feet. Both structures are pre-engineered steel buildings with masonry block walls. The pre-engineered buildings were designed by the building supplier, while the foundations, floor slabs and interior and exterior masonry walls were designed by the project structural engineer.

Site Soil Conditions

The site is located adjacent to the Christina River within the City of Wilmington, Delaware. The soils at the site, which
is located in the flood plain of the River, typically consist of alluvial deposits of varying depth, overlying residual soils and rock. Many of the older riverfront sites in the city, such as the one this project was constructed on, have been filled in the past with miscellaneous soils, ash and other materials to "reclaim" marsh lands.

Figure 2 illustrates the generalized site stratigraphy. Prior to construction of this facility in 1987, the surficial soils consisted of miscellaneous fill materials (Stratum B) placed over a layer of soft, compressible marsh deposits (Stratum C). The marsh deposits consisted primarily of high plasticity silt materials, which also contained some interlayered sands and varying amounts of organic materials. Some pockets of peat materials were also observed. Sand materials (Strata D and E) were encountered below the compressible soils, and were subsequently found to be underlain by residual soils (Stratum F).

Stratum A indicated in Figure 2, consisted of 3 to 6 feet of structural fill soils which was placed as part of the new construction in the building area in 1987. This structural fill was used to bring the area of the structures above the 100-year flood elevation.

Construction

Construction at the site began in February, 1987. During the construction, the design team expressed concern over the poor surficial soil conditions (Stratum B) which were exposed when earthwork began. The facility pavements were required to support considerable heavy truck traffic, and there were concerns over the ability of the miscellaneous fill to function as a suitable pavement subgrade.

The civil site designer recommended retaining a geotechnical engineer to evaluate these conditions, and Duffield Associates was retained to provide recommendations for the design and construction of the pavements.

During a construction meeting, our project engineer expressed concern over the potential for settlement of the building due to the weight of the newly placed 3 to 6 feet of structural fill. As a result, we were requested to provide an evaluation of site conditions based on the eight test borings, which had been previously performed by the design team. While there had been no laboratory testing performed on the soil samples from the borings, Duffield Associates, based on their extensive experience on other sites in this riverfront area, was able to extrapolate the properties of the marsh deposits.

<table>
<thead>
<tr>
<th>STRATUM</th>
<th>APPROXIMATE THICKNESS (FT)</th>
<th>GENERALIZED DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3-6</td>
<td>Structural Fill - Fine to coarse sand with trace gravel</td>
</tr>
<tr>
<td>B</td>
<td>3.5-9</td>
<td>Miscellaneous Fill - Various types of fill soils</td>
</tr>
<tr>
<td>C</td>
<td>5-24</td>
<td>High plasticity silt with trace to little sand, varying amounts of organics with some peat in some samples</td>
</tr>
<tr>
<td>D</td>
<td>3.5-10</td>
<td>Fine sand with some lenses of organic silt and some pockets of peat</td>
</tr>
<tr>
<td>E</td>
<td>10-27</td>
<td>Fine to coarse sand with varying amounts of silt and gravel</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>Residual soil; derived from the weathering of rock.</td>
</tr>
</tbody>
</table>

![Fig. 1 Layout of the buildings](image-url)
Preliminary settlement analysis performed by our firm indicated that approximately 5 to 10 inches of settlement could be expected from the structural fill which had been required to achieve the building grade. As a result, the geotechnical engineer recommended the following:

1. Pile support the entire structure, including the floor slabs; or
2. Preload (surcharge) the site prior to building construction to reduce post construction settlement.

Due to economic and time constraints (recall that the owner had limited time to vacate their original facility), the design team decided that options 1 and 2 could not be implemented. We indicated that if these options were not acceptable, the building structural and facade systems should be designed to accommodate the estimated settlements. Specifically, it was recommended that the floor slabs not be structurally connected to the pile supported foundation elements, and that negative skin friction (due to the expected settlement of Strata A, B, and C) be considered in determining the pile capacity.

While we provided a design section for the site pavement, we were not retained by the design team for any further services related to the design or construction of the structure, which was eventually completed in early 1988.

BUILDING EVALUATION IN 1994

In 1994, we were contacted by the owner and requested to visit the site to review reported settlement problems in the structures. At that time, observations indicated that significant settlement of the floor slabs had occurred, as well as cracks in the masonry walls. The owner also reported functional problems with doors installed in the interior masonry walls and complained of a leaking roof in the store area. Duffield Associates was requested by the owner to evaluate the conditions of the structure and foundations and to provide recommendations for possible remedial measures.

Scope of the Evaluation

Based upon this request an evaluation was completed which included the following:

- Performance of an elevation survey of the floor slabs and foundations of both buildings
- A review of the condition of the structures including the steel frames, the interior and exterior masonry walls, the floor slabs and other miscellaneous structural components.
- Performance of three Standard Penetration Test borings (two inside the building and one immediately outside), for the purpose of obtaining soil samples, and additional information regarding the subsurface stratigraphy.
- Performance of consolidation testing on samples of the Stratum C soils to determine their compressibility and time rate properties.
- Performance of a structural analysis to evaluate the effects of the differential settlement which had occurred on the structural frames.
- Performance of settlement analysis based on the stratigraphy and the results of the consolidation testing, to estimate the magnitude and rate of additional settlement.
- A review of the pile driving records.

Results of the Evaluation

Duffield Associates' evaluation resulted in the following determination for the various structural elements of the buildings:

Floor Slabs. Significant total and differential settlement had taken place in the floor slab in both structures. This settlement is illustrated in Figure 3 which shows the results of the elevation survey of the building floors.

The recommendation (in 1987) to isolate the floor slab from the pile supported foundation elements was not implemented. Review of the construction drawings indicated that the floor slab had been connected to pile supported perimeter grade beams and rested on pile supported caps, while it "floated" over the subsoils in the interior of the building. The result of this design was relatively large differential settlement over relatively small distances, especially in the south end of the store area, (see Figure 3). This resulted in a very noticeable "dish" or depression in the floor slab.
Analysis indicated that settlement of the subsoils, due to the weight of the structural fill placed in 1987, was not complete at the time of the 1994 evaluation. Based on the data obtained, it was estimated that as much as 4 to 5 inches of additional settlement might take place in this area over the next 8 years, following 1994. The approximate area in which this additional settlement was expected to occur is shown in Figure 4.

![Fig. 4 Area of expected future settlement](image)

**Pile Supported Foundations.** The 1994 post construction survey indicated that many of the pile supported foundations had experienced settlements ranging from less than one inch to as much as 8 inches (see Figure 5).

![Fig. 5 Pile foundation settlements at column locations](image)

Of the thirty structural columns supporting the store building, half were observed to have settled more than 3 inches. Of these, 12 columns had settled more than 4 inches and a total of 8 had settled more than 5 inches. Only 29 of the 40 columns in the shop building were accessible for the survey. Of these, a total of 8 columns had settled more than 3 inches, 6 had settled more than 4 inches and 4 had settled more than 5 inches.

Pile driving logs prepared during construction were reviewed by our firm as part of this evaluation. The timber piles which were utilized were to be driven to a 20 ton capacity based on the Engineering News Record (ENR) formula, according to the contract documents.

Review of the pile logs (which were apparently prepared by a "testing agency") and a comparison with the site stratigraphic information, indicated that many of the piles apparently did not penetrate into the competent soils (Strata D and E). While the logs indicated that the ENR criteria had been met over the last foot, calculations of the pile tip elevation from construction records indicated that the piles had not necessarily been driven into the sands of Strata D or E. In other words, a significant number of the piles appeared to be "floating" in the Stratum C soils, which were undergoing compression due to the weight of the structural fill placed in 1987 to raise the site.

This information, in conjunction with the results of the settlement analysis (which indicated that portions of the subsoils would continue to settle in the future), lead to the conclusion that many of the pile supported foundations would continue to settle in the future. The results of further analysis indicated that continuing differential settlement would cause additional structural members to be overstressed under design load conditions.

**Interior Masonry Partition Walls.** Review of the construction drawings indicated that the two masonry partition walls, located on each side of the building connector, had been constructed directly over a 4-inch thick concrete floor slab, which "floated" on the underlying compressible soils. The floor slab which supported the masonry wall had experienced large differential settlements of some portions of the wall. Other portions of the wall, which were located near pile supported foundations, experienced much less settlement, causing relatively large differential settlements and step and shear cracking in the walls.

Because additional settlement was projected in the area of these walls, additional damage to the walls was expected, if the walls were allowed to remain in place.

**Structural Frames.** The results of our structural analysis indicated that the observed differential settlement and the design load conditions specified by the building code might result in overstressing of the structural frames along two of the column lines in the store structure. Further, the estimated future settlement, in combination with the design load conditions specified by code, was project to result in overstressing of an additional four column lines in the structures.
The roof leaks in the store area were determined to be a result of impeded drainage on the roof due to differential settlement of one of the pile foundations supporting the structure.

Perimeter Walls. The perimeter masonry walls were observed to be in generally good condition, considering the relatively large differential settlement which occurred in some areas along these walls. The building perimeter walls were constructed over a pile supported grade beam. However, the pile caps supporting the wall had been determined to have settled differentially.

In one case, a differential settlement greater than 2-1/2 inches had occurred along an outside wall over a distance of 25 feet (which is much greater than that typically considered tolerable for a masonry wall). The settlement was noticeable on the exterior of the wall, with some minor cracking of the masonry wall; however, the wall control joints generally seemed to be effective in reducing cracking of the wall, even with the large magnitude of differential settlement.

Remedial Program.

The development of a remedial program included reviewing the results of the evaluation with the owner. These discussions included the cost of various repair/corrective alternatives and the risk of future maintenance due to continuing differential settlement. As a result of these discussions, a remedial program was developed, which is discussed below.

Floor Slabs. Several alternatives for remediating the floor slab condition were considered. These alternatives ranged from performing relatively inexpensive "cosmetic" repairs to the existing concrete slabs, to a complete removal and replacement of the slabs. The major concern in addressing the slabs was how the settlement which was expected to occur in the future would be accommodated. The use of a lightweight fill to reduce settlement beneath a reconstructed floor slab system was also considered.

The alternative selected by our firm's team of geotechnical and structural engineers and the owner for the store area involved the construction of an elevated system of modular floor panels, (similar to floor systems sometimes used in computer rooms). This type of floor (illustrated in Figure 6) is supported by a series of vertical supports, which can be adjusted in the future to accommodate the continuing differential settlement. The supports, which can be accessed by removing a floor panel, can be adjusted with a wrench to keep the floor "in level". The appeal of this system was that it could be readily maintained by the owner's personnel, and would not require retaining outside assistance to relevel the floor in the future.

In lieu of installing the raised floor in the workshop area, it was decided to perform relatively minor repairs on the floor slab since the differential settlement were less severe and less noticeable in this area.

![Fig. 6 Schematic of adjustable floor.](image)

Foundations. Our study team concluded that the pile foundations were not performing as intended, and that many piles may not have penetrated a suitable bearing stratum. Underpinning of the existing foundations (using pin piles or augercast piles) was considered briefly. However, the estimated engineering and construction costs for this type of remedial action were determined to be prohibitively high. Continued settlement of many of these foundations in the future is expected at a reduced rate. Therefore, ongoing monitoring of the foundation elevations was recommended.

Structural Frames. The stresses in the structural frames due to the differential settlement were relieved by unbolting the braces connected to the bottom chord of the affected trusses, allowing them to move and "equilibrate." Subsequently, the bolt holes were enlarged and the braces were reconnected in the displaced configuration. Future observations of the foundation elevations will be used to monitor the distortion of the structural frames, and evaluate whether similar remedial action will be necessary in the future.

The area of the roof leak was repaired by raising the end of selected truss purlins in the affected area and shimming them to restore positive drainage away from the ridge of the roof.

Interior Masonry Partition Walls. It was expected that any repair of these walls would be short-lived due to the expected continuing differential settlement. The recommended remedial action involved removing the interior masonry wall from the shop building and replacing it with a conventionally framed metal stud and drywall wall system. The masonry wall in the store area remained in place, but is screened by drywall on both sides so that it is not visible.
LESSONS LEARNED

On this project, the design architect and his structural engineer apparently did not feel that it was necessary to retain a geotechnical engineer to assist with the design of the structure. The lack of consideration of geotechnical factors and their effect on the performance of the structures caused additional cost to the owner in terms of maintenance and remediation. The remedial activities described above were completed in 1996.

The lessons learned from this project include:

1. Settlement of soft soils does occur and should be addressed as part of the design of structures to be constructed over such soils.

2. Pile foundations can experience settlement. In many instances, the construction records for this project indicated that piles were probably not driven adequately into a competent bearing stratum. However, it was also apparent that piles driven into competent soils had settled from the combined building loads and negative skin friction.

3. The use of control joints in the perimeter masonry walls was very effective in reducing the effects of the large differential settlements which were experienced.

4. The results of the building evaluation indicate that steel framed structures can undergo significant settlement and still remain functional. In this case, many of the observed differential settlements were larger than those typically considered tolerable. However, the structures remained serviceable with some maintenance.

5. If “mixed” foundation types are to be used in a structure, isolation of the pile supported portions and a “floating” slab should be utilized to “control” the location of the differential movement.

6. The elimination of a geotechnical engineer from the original design process no doubt reduced the cost of the original design. However, the owner was apparently not aware of the decision or the implications associated with this decision. The cost of a design phase geotechnical evaluation was spent many times over in the maintenance and remedial construction costs.

One of the most important lessons learned from this project is the importance of retaining a qualified geotechnical engineer as part of the design team. On this particular project, geotechnical assistance would have been beneficial to the owner in the following areas:

- Assist with the evaluation of alternatives and risks in selecting a design; assist with design of the structure
- Provide review during construction

Providing assistance during site acquisition can help the owner and design team understand the issues and risks involved with purchasing/selecting a specific site. During the design phase of the project, the geotechnical engineer can assist the owner and the design team by making them aware of the risks involved and determine how much risk the owner is willing to tolerate.

Finally, a qualified geotechnical engineer should be retained to review construction and confirm the findings of the geotechnical evaluation. In this case, recognizing and resolving anomalies (i.e., actual pile driving depth compared with test boring results), is part of the geotechnical engineer’s role in the construction phase of the project.