Controlled Subsidence during Pile Driving

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ABSTRACT The Provincial Building located in the downtown core of Sudbury, Ontario is an 11-storey concrete frame building supported on long driven concrete piles. At an immediately adjacent site, the general ground surface settled 0.9 m over a brief time period during pile driving for the foundations.

The subsoil stratigraphy beneath the Sudbury Provincial Building comprises 6 m of loose recent alluvial material with a groundwater table 1 to 2 m beneath the ground surface, followed by 12 m of soft to firm silty clay. Beneath this clay layer and continuing to a depth of 46 m is a stratum of 27 m of loose to dense fine becoming coarse silt. Bedrock is at a depth of 65 m with 15 m of dense till over bedrock.

Soon after pile driving began at the adjacent Civic Regional Building, water was noted rising adjacent to the piles. During the operation when a damaged pile was removed, water gushed freely from the hole. Up to 0.9 m of subsidence was recorded with the center of the settlement occurring near the pile driving operation. The zone of influence for this subsidence extended well beyond the property lines into adjacent roadways; fortunately no buildings were immediately adjacent to this site. The lateral movement of piles close to the center of the zone was measured up to 150 mm toward the center of the zone of influence.

Because of the problem on the adjacent building, it was known that a similar subsidence could occur at this site. To avoid complications of the subsidence effect of this construction on the Civic Regional Building the foundations for the Provincial Building were constructed immediately after the pile driving was completed for the Civic Regional Building. By modifying the construction sequence the overall subsidence was reduced to 15 percent of that experienced at the Civic Regional Building.

INTRODUCTION

The Ontario concept of Regional Government in the mid 1970's
gave rise to the Sudbury Civic Square project. This project included a Civic Regional Building and a Provincial Building. The project in the downtown core consisted of a 5-storey single parking basement level structure with adjacent West Tower Building and a proposed future 11-storey Provincial Building. These proposed structures were to wrap around the existing Bell Canada Tower a 5-storey single basement office complex.

The site had been used as a parking lot for several years after demolition of smaller commercial type stores and residential housing. This area had, during earlier times, been the site of Junction Creek that meandered through the development. The flood plain occupied most of the area prior to infilling and redirecting the creek through a concrete culvert. The Bell Building immediately north of the proposed buildings and forming part of the complex was founded on a raft below a single basement level (see Figure 1).

This paper briefly discusses the geological conditions at the site and describes the discovery of the subsidence settlement conditions during the driving of piles for the Civic Regional building (Figure 1). The treatment of the foundations for the Provincial Building in this problem area is presented and the successful results are discussed.

SUBSOIL DATA

The geology of the Sudbury area is noted for its extreme variations in bedrock elevation soft clays and loose silts. The geology is further complicated by silts and clayey silt whose capacity is difficult to predict when subjected to dynamic loading, i.e., pile driving.

The original design concept for the Provincial Building and Civic Regional Building was to incorporate a raft foundation for the major buildings and spread footings for the connecting links. The initial investigation indicated that it would probably be more economic to support the building on piles. Further investigations to select pile founding levels were subsequently undertaken.

The subsoil was found to be reasonably uniform over the entire site, with the exception of the depth of fill and alluvium overlying the firm silty clay. This alluvium was found to vary from 2 to 6 meters in depth with the deeper depths reflecting old creek channels or flood plains that had traversed the site in a random fashion. Figure 2 shows a typical subsoil profile consisting of 6 meters of fill and recent alluvial material over a firm silty clay to a depth of 18 meters; below 18 meters the clay grades to a stratified silt gradually becoming more sandy and at 30 meters changes to a silty sand. To the 40 meters depth the silt and sandy silt exist in a compact to dense state. Below 40 meters and to 46 meters, a layer of loose silty sand was encountered overlying dense sand, gravel and cobble till. Below 46 meters, bedrock was not proven, but is anticipated at 65 meters depth.

The geotechnical properties of each layer are included in abbreviated form on Figure 2. Figure 3 indicates typical
gradings for representative depths. The groundwater level in the upper fill and alluvium was near old creek level some 2 meters below existing surrounding ground surface. The sand, gravel and cobble till at a depth of 46 meters showed a piezometric head at least 1 meter above the existing ground surface, i.e., Elevation 257 meters.

FOUNDATION CONSIDERATIONS

Prior to construction the designers decided to eliminate the raft and utilized driven piles. Experience in this area showed low displacement H piles would penetrate 3 to 4.5 meters beyond
FIG. 2 Subsoil stratigraphy.

the depth of displacement piles. Because of the potential cost saving displacement piles were considered most practical. Based on this requirement it was estimated that piles carrying nominal loads, i.e., 445 kN on a 250 mm and 710 kN on a 300 mm displacement pile would meet refusal at an average depth of 35 meters or Elevation 221 meters. This depth was determined by the standard penetration test results in the boreholes and to a
larger extent by the dynamic cones driven at the base of the boreholes. Local experience had shown that typical pile 'refusal', i.e., 15 blows/25 mm would be achieved for displacement piles 4.5 to 6 meters below the refusal to driving of the dynamic cone i.e., more than 100 blows/300 mm.

The actual load carrying capacity of the piles was to be determined by load tests, however, the most economic pile for the deep depths was one that was driven to a capacity equal to the structural capacity of the pile. The piles selected were precast concrete piles with quick attach patented full moment splices. The nominal 200 mm pile was to carry 620 kN while the 300 mm size should be driven to carry maximum loads of 1020 kN. These capacities were to require sets of 20 blows/25 mm with the maximum safe capacity to be confirmed by the load test.

Test Results Three piles were selected for testing. The result of these tests is presented as Figure 4. It can be seen that the 300 mm piles were capable of carrying a 1020 kN design load and the 200 mm pile obtained the necessary safe capacity of 620 kN.

![FIG. 4 Pile load test results.](image)

PILE DRIVING - CIVIC REGION BUILDING

Pile driving began with the driving of the test piles January 13 and 31, 1975. Production driving commenced late January of 1975. During the early days on site, significant problems associated with pile breakage occurred and the driving schedule was very much behind by mid February when it was decided to bring
a second pile driver on site. From January to mid February only 20 of the 437 piles for the civic region complex had been driven. The initial hammer, a Linkbelt 520 rated at 35 kJ was supplemented with a Linkbelt 440 (24 kJ). Both hammers when checked with the Pile Driving Analyser were delivering up to the designated 24 kJ of energy to the pile.

By March 5, both units working side by side were driving up to 6 piles per day. On one pile a maximum of 2000 blows was required to penetrate the upper 0.3 to 0.6 meters of frozen ground, however, this was exceptional as most piles penetrated the frost zone with less than 150 blows.

During the first week of March, a local depression around the pile drivers, approximately 36 meters in diameter and 1.2 meters in depth with a volume of 1200 cubic meters was recorded. This depression occurred rapidly, i.e., within 2 days. Elevations taken on catch basins in the depression indicated a settlement of 1 meter below original level. The extent of this subsidence is shown on Figure 1. As this depression was forming driving continued. Silt laden water was noted to be flowing up around some of the piles. An analysis of the silt showed that it corresponded to the grain sizes of the material from the deeper silt strata below 21.5 meters.

Piles within the depression moved more than 200 mm laterally towards the center of the zone of influence and there was concern for their integrity. A retapping program carried out on the piles that were obviously affected showed that their original resistance to driving remained unchanged.

Figure 5 and 6 indicate some of the magnitude of the settlement; Figure 7 shows the intensity of the piles, although no cap contained more than 8 piles.

Speculation as to what was the source of the settlement and the consequences for continuing work were of immediate concern. To determine if the settlement was deep-seated or occurred as a result of consolidation of the upper loose fill and alluvial material, settlement points were installed at ground surface, within the fill/alluvium and into the silty clay. During installation of the settlement gauges a pile suspect of being damaged was withdrawn from the position shown on Figure 1 and water gushed from the 18 meter deep hole for a 38 to 48 hour period and settlement of 1 foot over large (30 meter cone) area resulted.

It was obvious that the pile driving was causing the problem regardless of where the problem originated from. To reduce this effect, the pile drivers were separated to opposite ends of the site and pile driving was restricted to 1 or 2 piles a day per pile group. Piling continued until the 437 piles were in place and little, i.e., less than 25 mm of movement was detected over the remainder of this site. No pattern of movement at depth could be obtained from the settlement points.

Based on all the data that could be assembled, it was possible to show that serious damage could result to structures within 30 meters of any similar occurrence. Since the adjacent Provincial Building would be constructed within this zone there was concern that damage to the Civic Regional Building could occur during construction of the Provincial Building.
The foundations for the Provincial Building were scheduled to begin construction 18 months after the completion of the Civic Regional Building. Measurements of the potential zone of influence in which subsidence could occur showed that construction of the Provincial Building would adversely affect
the Civic Regional Building. The owner was advised that it was imperative to drive the piles for the Provincial Building immediately, i.e., before the pile caps and superstructure for the Civic Regional Building were in place. This recommendation was accepted and the objective was to cause minimal subsidence in the area of construction and to avoid subsidence in the area of the adjacent structure.

The experience at the Civic Regional Building indicated that concentrated pile driving was the main contributing factor to subsidence. To reduce this subsidence, pile drivers should be kept as far apart as possible. The structural consultant agreed that instead of the heavily loaded concentrated pile support system proposed, that a wide spread pile spacing incorporating grade beams was possible. A redesign of the pile layout therefore eliminated large pile groups.

A hold was placed on construction in the adjacent area of the Civic Regional Building and by carefully spacing and separating the driving of piles the overall settlement during driving was measured to be less than 150 mm.

Prior to beginning driving six settlement points were installed in the Provincial Building area. As for the Civic Regional Building at each location the gauges enabled an assessment of subsidence at the ground surface, in the alluvium and fill and below the silty clay. A review of this data showed that only minor movements could be attributed to the fill and alluvium and that the major settlement took place below the silty clay layer.

Vibration Monitoring. Throughout the entire driving program a vibration consultant was retained to assess the vibrations and potential damage resulting from pile driving. The results of this monitoring showed that at no time did maximum vibration
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FIG. 8 Damage adjacent to roads.

FIG. 9 Damage adjacent to roads.
amplitudes reach 50 mm per second at a distance of 5 meters from the pile. Apart from significant cracking to adjacent roads no off site damage was recorded for this project (Figure 8 and 9).

**Long Term Performance** Monitoring of the site over the past 10 years shows no adverse effect from the subsidence to either of the projects described or to the neighbouring Bell Building. It is interesting to note that no other buildings in this area have been or are likely to be founded on piles, since the construction of the Civic Center Buildings.

**Related Comments** It was not possible to accurately assess the source of the large measured subsidence at the adjacent Civic Regional Building since instrumentation was not in place in this area until the movement was virtually complete. At the Civic Regional Building it could have been argued that the upper fill and the alluvial material were loose initially and could have been a potential source of subsidence. Tests carried out in these materials after the subsidence showed an increased density and decreased water content. This could have resulted from vibration induced consolidation and densification or it could also have resulted by driving a large number of displacement piles. The silt encountered at a depth of 40 meters is described as loose and possibly the driving could have resulted in vibrations that densified this material - water was noted emerging from extracted pile holes and this could have originated at this level. At the Provincial Building it was clearly established that the subsidence was caused by deep seated densification of the silt.

**CONCLUSIONS**

1. The choice of pile type should be carefully related to all site conditions and economics should not be the prime consideration.

2. The potential for densification of loose layers of cohesionless material can be of greater significance than is often considered for most sites.

3. Ground control measurements must be well thought out and be in place prior to construction if they are to provide the control and information to warrant their cost.

4. The long-term effect of the subsidence in this case was negligible for both the constructed buildings and for adjacent property.

**REFERENCES**

