Computed and observed ground movements during top-down construction in Chicago

Mouvements de terrains calculés et observés en construction descendante à Chicago

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ABSTRACT: Two detailed case studies of deep excavations in Chicago made with top down techniques are presented. The importance of considering all aspects of the construction process when estimating ground movements is emphasized. Detailed construction records were maintained at both sites. Inclinometers located within the walls, close to the walls and 7 m from the wall provided lateral movements throughout construction. Ground surface settlements were obtained by optical survey of several hundred observation points at each project. In addition, one of the projects included 88 strain gages installed in the floor slabs to measure time dependent responses of the concrete slabs used as lateral support for more than four years. The movements are presented in relation to construction activities and causes of incremental movements are identified. The lateral movements that arose from cycles of excavation and bracing accounted for approximately one-quarter and one-half the total movements at the two sites. Of these, field performance data and results of numerical simulations showed that approximately 40% of the movements arose from the time-dependent responses of the concrete floor slabs.

RÉSUMÉ : Deux études de cas détaillées d'excavation profondes réalisées à Chicago en construction descendante sont présentées. L'accent est mis sur l'importance de prendre en considération tous les aspects du procédé de construction. Des registres de construction détaillés ont été maintenus sur les deux projets. Des inclinomètres situés dans les murs, à proximité des murs et à 7m du mur ont mesuré les déplacements horizontaux tout au long de la construction. Les affaissements de surface ont été observés à l'aide d'un relevé topographique optique comprenant plusieurs centaines de points pour chaque projet. De plus, l'un des projets comprenait 88 jauges de déformations installées dans les dalles de plancher pour mesurer les réponses dans le temps des dalles de béton utilisées comme supports latéraux pendant plus de quatre ans. Les mouvements sont mis en relation avec les activités de construction et les causes des mouvements progressifs sont identifiées. Les mouvements latéraux causés par les cycles d'excavation et de contreventement ont représenté environ la moitié et le quart des mouvements totaux sur les deux projets. Pour ceux-ci, les résultats des tests sur le terrain et des simulations numériques ont montré qu'environ un tiers des mouvements était causé par les réponses dans le temps des dalles de planchers en béton.

KEYWORDS: Excavation, top-down support, ground movements, clays, time-dependent concrete response

1 INTRODUCTION

Use of top down construction has increased as more developers have seen the benefit of taking the excavation portion of a project off the critical path. Top down methods use permanent walls and flooring systems as temporary support and thus the support systems are very stiff. Yet, there are conflicting data concerning whether resulting movements are smaller than those associated with bottom-up methods. For example, Long (2001) observed no discernible difference in the performance of internally supported, anchored, or top-down systems based on examination of 296 excavation case studies. Kung (2009) reported results of 26 excavations made through Taipei silty clay which showed the maximum lateral wall deflection induced by the top-down methods were 1.3 times larger than that induced by bottom up methods. These observations are surprising given that the floor slabs are in theory much stiffer than either cross-lot braces or ground anchors, and that it is not possible to overexcavate the soil – i.e., make a deeper cut than planned so that the support system is essentially more flexible than planned in design - during construction since one must cast each floor on the ground.

This paper summarizes two case studies of deep excavations in Chicago made with top down techniques. Detailed construction records were maintained at both the Block 37 and One Museum Park West (OMPW) projects. Performance during construction is illustrated with results of inclinometers located close to the walls and optical surveys of points on the ground adjacent to the excavations. In addition, one of the projects included 88 strain gages installed in the floor slabs to measure for four years the time-dependent responses of the concrete slabs used as lateral support. The movements are presented in relation to construction activities at both sites and causes of incremental movements are identified. It is shown that the movements that occurred during cycles of excavation and bracing are small, and about 40% of these movements are attributable to the time-dependent responses of the concrete slabs. The importance of considering all aspects of the construction process when evaluating movements is emphasized.

2 SUBSURFACE CONDITIONS

The subsurface conditions at the two sites are summarized in Figure 1 which shows the natural water contents and undrained shear strengths found from results of site investigations at each location. The surficial layer is an urban fill material consisting of sandy soils and construction debris. Underlying the fill material is a sequence of glacially deposited clays. The first two layers are soft to medium stiff clays which are very similar mineralogically, but exhibit different geotechnical characteristics due to the type of glacial deposition. The Blodgett stratum underlies the urban fill and was deposited in a supra-glacial environment, which include glaciolucustrine clays and melt-out and flow tills (Chung and Finno, 1992). Because of this complicated depositional environment, the Blodgett generally has variable geotechnical characteristics, including water content, strength and stiffness. A desiccated crust is often present on top of the Blodgett stratum. At these sites, the crust is relatively thin, and in some cases is not present at all. Underlying the Blodgett stratum is a medium stiff clay, called the Deerfield stratum. This stratum exhibits much more uniform geotechnical characteristics than the Blodgett because the Deerfield was deposited as a basal melt-out till or a waterlain paratill. The stiff Park Ridge clay underlies the Deerfield layer. It is generally a little more overconsolidated than the upper clays, with an OCR of about 1.5. A deposit locally known as “hardpan” is found beneath the Park Ridge stratum. The soils in the hardpan are very stiff to hard and consist of silty clays to clayey silts and contain occasional lenses of sandy soils. These soils are basal tills and overconsolidated.

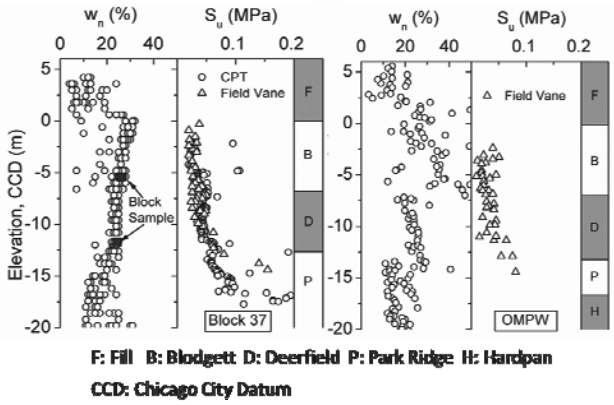


Figure 1. Subsurface conditions

3 BLOCK 37 PROJECT

Lateral support for the Block 37 excavation consisted of a 0.9 m thick reinforced concrete slurry wall and four levels of reinforced concrete floor slabs. After installation of the slurry wall, existing foundations from previous buildings were removed. These potholing activities were extensive near the north end of the excavation, and excavations reached as deep as 6 m. After the abandoned foundations and walls were removed, the excavations were backfilled.

Thereafter the excavation progressed in stages to the levels of the four basement floors (B1, B2, B3 and B4). Because the “ground” slab was placed after slab B1, the slurry wall was cantilevered with an unsupported length of about 7 m before any lateral support was placed. Thus this excavation deviated from an ideal top-down construction system because the lateral support was not installed prior to any significant excavation. The contractor made the decision to delay placement of the ground surface slab on the basis of construction expediency. A complete description of the activities at the site and performance of the excavation is found in Kern (2011).

3.1 *Ground movements during construction*

The development of ground movements during construction is summarized in Figure 2. The optical survey points and inclinometer were located adjacent to the north wall of the excavation. The settlements are typical of the maximum values measured along this side of the excavation. The horizontal movements were taken from an inclinometer located 1 m behind the slurry wall near its center and were taken from elevation – 9 m CCD. Lateral movements versus depth will be discussed in the next section. Also shown on the figure is a record of the construction activities so the causes of the movements are apparent.

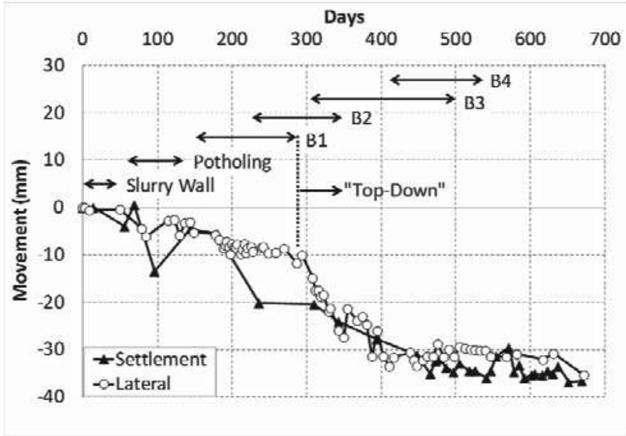


Figure 2. Settlements and lateral movements at Block 37

The maximum settlement and lateral movement observed at this section was 36 mm. As is apparent from the figure, significant ground movements developed during both the potholing activities and the first portion of the excavation when the large cantilever stage existed as the contractor excavated to the B1 slab level. These activities caused about 60% of the settlements that developed throughout the entire construction process. This large percentage was caused by the contractor’s decision to start the top-down process after the first level basement was constructed. The removal of the old foundations and slabs also contributed to the relatively large movements observed along this wall.

3.2 *Lateral movements adjacent to wall*

Typical distributions of lateral ground movements with depth are shown in Figure 3 for inclinometers located 1 m and 7 m from the wall. These inclinometers were installed prior to any construction at the site and thus indicate the complete lateral response. The large influence of the potholing and initial cantilever stage of the excavation is seen clearly in the results.

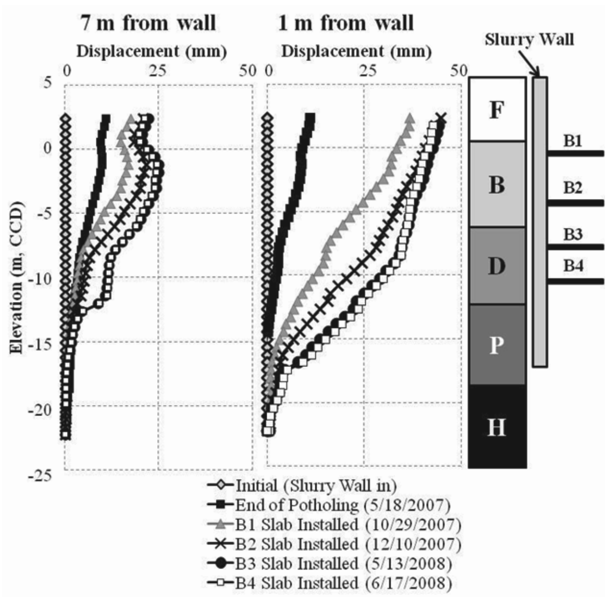


Figure 3. Lateral ground movements at Block 37

4 ONE MUSEUM PARK WEST PROJECT.

The One Museum Park West project involved constructing a 53-story reinforced concrete tower with a central core and four or five basement levels that extended approximately 15.3 m below grade. The central core was excavated using a circular cofferdam, consisting of a sheet-pile wall and horizontal ring beams for internal bracing. The construction of the tower core was performed in a conventional “bottom-up” manner. The basement was constructed with steel beam reinforced concrete secant pile walls using top-down construction procedures. After leveling the site, the perimeter wall was installed and caisson foundations constructed. After the central core cofferdam was built, the excavation of the remainder of the site is being made with “top-down” construction methods. The perimeter secant pile wall is utilized as a permanent load bearing wall. Lateral bracing is provided by 4 or 5 levels of permanent floor slabs, depending on the location within the structure. After the ground level slab was cast integrally with the slurry wall, excavation proceed top-down by excavating to the bottom of the second level floor slab, casting that slab integrally to the slurry wall, and repeating the process until the final excavation depth was reached. Detailed descriptions of the construction and performance of this project are found in Sarabia (2012) and Arboleda (2013).

The development of ground movements during construction is summarized in Figure 4. Again, both settlements and lateral movements are represented in the figure. In this case, only the settlements provide a complete record of the ground response during construction. The inclinometers were located within 1 m of the secant pile wall at all locations, and were damaged as the wall was installed. Replacement inclinometers were initialized prior to the start of top-down excavation, so these data do not reflect deformations that developed as the wall and caissons were installed, or as the central core cofferdam was constructed. The data for the lateral movements were taken from the location of the maximum lateral movement recorded by the inclinometer, in this case, from elevation -8 m CCD. The settlements are typical of the maximum values measured along the west side of the excavation. Also shown on the figure is a record of the construction activities so the causes of the movements are apparent.

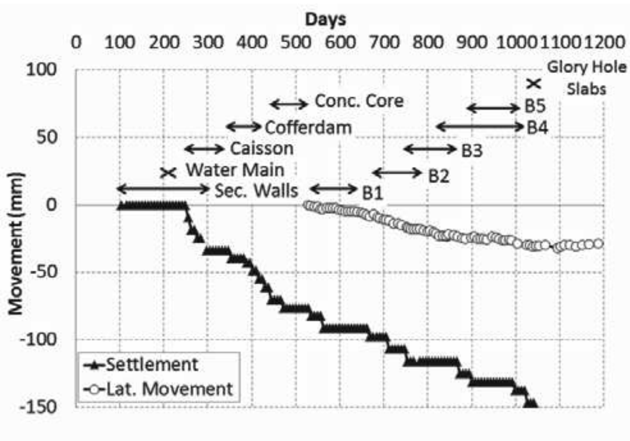


Figure 4. Settlements and lateral movements at OMPW

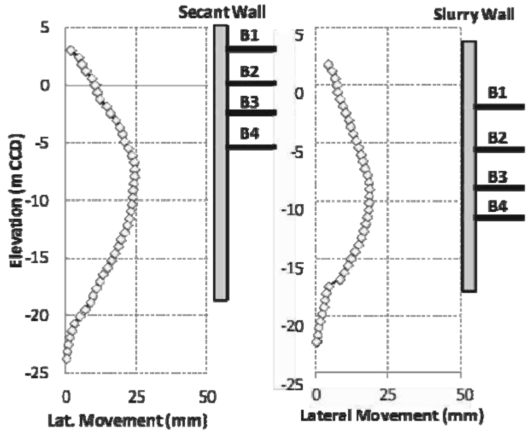
The maximum settlement observed at this section was 150 mm and the maximum lateral movement was 30 mm. As is apparent from the figure, significant ground movements developed throughout construction. The portions of the settlements that occurred during different phases of construction are summarized in Table 1. The activities before the top down portion of the project started resulted in 75% of the total settlements observed during construction.

Table 1. Settlements during construction activities

Construction activity	Settlement (mm)
Secant pile wall installation	11
Caisson installation	12
Water main relocation	5
Central cofferdam construction	12
Top-down construction	13

5 WALL MOVEMENTS DURING EXCAVATION

The lateral deformations that were recorded at OMPW only reflect those that occurred during top-down construction. Data from an inclinometer located in the middle of the west wall are shown on Figure 5. Also shown on the figure are the lateral movements that developed at Block 37 during the top-down phase of that construction, i.e., those after slab B1 was cast.



OMPW Block 37

Figure 5. Lateral movements during top-down excavation only

The trends in these data reflect expected responses for an excavation made using top-down methods with very stiff walls and supports. Very little lateral movement is observed at the uppermost slab which was cast at the ground surface. The normalized maximum horizontal movements (movement/depth of excavation) were 0.14% and 0.2% at the Block 37 and OMPW sections, respectively. These values are more in line with what one would expect from a very stiff excavation with no overexcavation. However, it is clear that movements developed at both sites as a result of other construction activities or procedures that were not employed with the goal of minimizing ground movements. When using precedent for a first order estimate of expected ground movements for a top-down procedure, these data provide useful estimates. One should not indiscriminately use performance data without considering all activities that occurred during construction.

6 TIME-DEPENDENT RESPONSES OF FLOOR SLABS

The concrete floor slabs that serve as lateral bracing for these two projects were cast integrally with the support walls. As such, the floor slabs contracted as the concrete cured and crept under load. This time-dependent component of movement contributed to the wall deformations and analyses were conducted to evaluate the magnitude of this effect. Eighty-eight vibrating wire strain gages were cast into the OMPW slabs at four levels and at five sections so as to directly measure the strains in the slab that developed over time. Detailed descriptions of the instrumentation and results of analyses are given in Arboleda (2013).

To illustrate the influence of the time-dependent properties of concrete on the lateral movements of the secant walls, 3D finite element simulations of the top-down construction process were conducted using SAP2000. The nonlinear time-dependent concrete effects of shrinkage, creep and variation of the modulus of elasticity with time were considered in the analysis. The analysis was performed in a step-by-step basis for the entire construction sequence using nonlinear stage construction without geometric nonlinearity.

Figure 6 shows the model after the first basement level was placed. The reinforced concrete columns and caissons were modeled as frame elements whereas the basement slabs, secant walls, foundation mat, corewalls, and interior shear walls were modeled as thin shell elements. The cross section of the secant walls consisted of concrete elements with embedded wide flange sections (W24, W33) and was modeled using an equivalent thickness based on the transformed section. Structural loads were applied, but lateral earth loads were not.

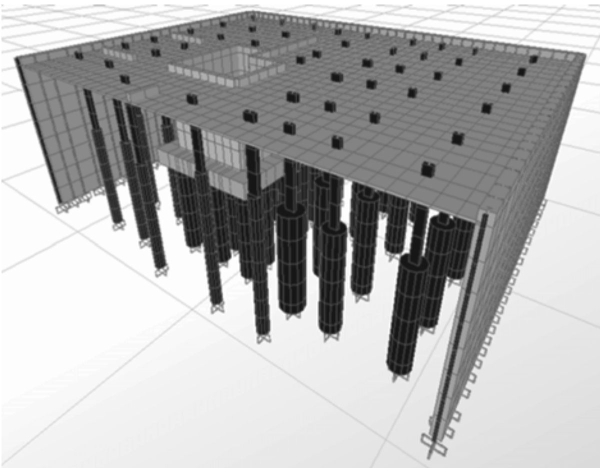


Figure 6. Model for time-dependent slab response at OMPW

The concrete was assumed isotropic with compressive strength taken from the as-built structural drawings and verified with the concrete reports provided by the contractor. The time-dependent behavior of concrete was included only for the basement slabs. The concrete properties were calculated based on standard concrete practice methods defined in ACI (2011) for a Poisson ratio of 0.2. The nonlinear variation of shrinkage with time was based on average values of the standard concrete practice codes: ACI 209, CEB-FIP 1990, AASHTO LRFD 2010, AS3600-2009, and NEN 6720.

The results of the analyses are given in Figure 7, where both the computed time-dependent movements of the walls at the end of each slab placement stage are compared to the total lateral movements of an inclinometer 1 m behind the wall. The lateral movements shown correspond to those that developed after the excavation to the first slab level was made, so that one can directly see the contributions of the time-dependent movements to the lateral deformations. About 40% of the lateral movements can be attributed to the time dependent effects of the concrete slabs.

7 CONCLUSION

Based on the results of the data and analyses summarized herein, the following conclusions can be drawn regarding these two excavations:

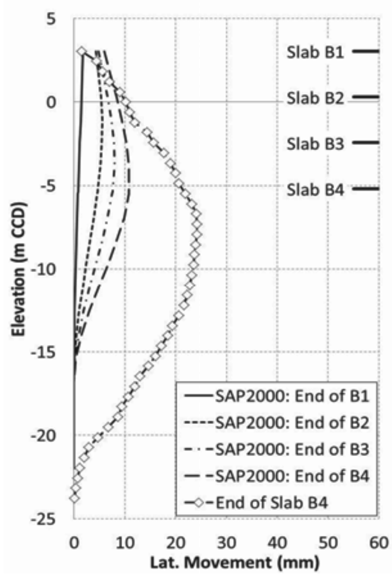


Figure 7. Computed time-dependent and observed lateral movements after slab B4 placed at OMPW

1. Top-down excavations in clays can be expected to result in normalized horizontal movements of approximately 0.15 to .2% when the uppermost slab is placed close to the ground surface so as to minimize the cantilever movements associated with the excavation process.
2. Of these “top-down” movements, approximately 40 % could be attibuted to the time-dependent response of the concrete floor slabs.
3. Other construction activities or expedient excavation procedures led to movements that constituted 60 to 75% of the total movements that developed during construction. Use of precedence in estimating ground movements must be tempered by a realization of other site activities that can lead to ground movements.

6 ACKNOWLEDGEMENTS

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