Risk Management Based Ground Deformation Monitoring during Queens Bored Tunnels Project

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Abstract. Ground, building and utility deformation monitoring is a well-accepted and required practice for underground construction works in urban environments. The availability of real-time monitoring data during construction allows stakeholders to stay ahead of potential problems, to make decisions prior to damage occurrence, and ultimately to reduce damage and cost risk. This paper presents the analysis of a comprehensive monitoring program carried out during the East Side Access Queens bored tunnels project in New York City. The project involved the construction of four near surface, closely spaced metro transit tunnels beneath the rail yards and mainline railroad tracks. The close proximity of the tunnels provides a unique opportunity to examine the influence of multiple closely spaced tunnel openings on ground deformation, particularly the accumulation of vertical surface deflection due to consecutive tunnels. The project also allows for a direct comparison between deformation monitoring techniques as both manual survey based monitoring and automated total station monitoring were used on the project. This paper will provide an overview of the monitoring program as a component of the risk management process on the project. The monitoring program will be described in detail and results will be presented. The paper also addresses potential improvements to risk-reduction through monitoring.

Keywords. tunneling, ground deformation, monitoring, risk assessment

1. Introduction

Underground construction works in urban environments require close monitoring of ground, building and utility deformations to minimize damage and reduce risk to the existing infrastructure. Real time deformation monitoring allows for the continuous assessment of the potential risk the underground construction work imposes to the existing infrastructure, and enables the contractor to make adjustments to the construction practice should intolerable risk situations arise. The East Side Access Queens bored tunnels project in New York City involved the construction of four closely spaced shallow tunnels in soft ground beneath an existing rail yard and mainline tracks (Figure 1).

Because the owner required that the rail yard and mainline tracks remain in service throughout the entire duration of the construction, extensive ground and rail deformation monitoring was performed. This paper will provide an overview of the monitoring program and selected results will be presented. Lessons learned and potential improvements to risk-reduction through monitoring are addressed.



Figure 1. Queens ESA launch wall configuration and tunnel drives.

2. Background

The four tunnels totaling 3,251 m in length (refer to table in Figure 1 for individual tunnel lengths) were constructed by the joint venture of Granite Construction Northeast, Inc., Traylor Bros. Inc., and Frontier-Kemper Constructors, Inc. in 2011 and 2012. Two 6.9 m (22.5 ft) diameter Herrenknecht slurry shield TBMs were used. The cross-section at the launch wall (Figure 1) illustrates the four tunnel configuration. At the launch wall, excavation of tunnel YL began at a depth of 22.9 m below the existing ground surface. Tunnel A began 11.9 m deep and tunnels D and BC 11.7 m deep. Tunnel YL was driven first, followed by tunnels A, D and BC. The ground conditions primarily consisted of highly variable glacial till and outwash deposits. The first 130 m of tunnel YL was excavated in fractured gneiss bedrock while the other three tunnels were excavated in soil. The project is described in detail in Robinson & Wehrli (2013a,b).

2.1. Risk Management and Tunneling

With the construction of four closely spaced and shallow tunnels excavated in soft, variable soil, the potential for ground deformation requires careful risk management. Preliminary analysis of the potential risks in the East Side Access Queens tunnels yielded a comprehensive monitoring program to closely monitor railroad tracks and facilities, underground utilities, buildings, bridges, streets and retaining walls.

An action level plan was developed to identify review and alert levels that required corrective measures to be implemented (review level) or stop the construction and conduct all necessary mitigative action to halt settlement or other differential movement (alert level) to avoid damage to existing structures and facilities.

2.2. Deformation Monitoring Program

Given the sensitivity of the existing nearby infrastructure including buildings, bridges and rail tracks, all of which were required to remain in uninterrupted service throughout the project, allowable settlement/heave ground deformation was very limited. Table 1 presents the review and alert levels used in the project for the infrastructure at risk.

 Table 1. Review and Alert Vertical Surface Deformation

 Levels

Infrastructure	Review Level [mm]	Alert Level [mm]
Buildings & Bridges	13 (0.5 in)	25 (1.0 in)
Street Pavement	19 (0.75 in)	38 (1.5 in)
TBM Launch Wall	25 (1.0 in)	63 (2.5 in)
Retaining Walls	19 (0.75 in)	25 (1.0 in)
Railroad Tracks*	15 (0.5 in)	38 (1.5 in)

*Approximate values; refer to Amtrak MW 1000 for specific response level ranges

As part of the monitoring program, both manual and automated total station (AMTS) surveys were routinely conducted to assess the ground and infrastructure deformation behavior in real time. A total of 380 manual survey and 573 AMTS monitoring points were deployed over the project site (Figure 2). The manual survey monitoring points were located in the Sunnyside Rail yard. Due to high train traffic and the manual monitoring approach yard, high frequency measurements were difficult to



Figure 2. East Side Access surface deformation monitoring layout.

achieve, resulting in a sporadic measurement frequency of at least one day between readings. The AMTS monitoring points were located within the mainline tracks with a measurement frequency of 10 readings per day. In addition, deep benchmarks, multiple-point borehole extensometers (MPBX), inclinometers and open standpipe piezometers were deployed to monitor ground deformation and ground water behavior. For brevity, only the manual survey and AMTS monitoring points are presented here.

Both the manual survey and AMTS readings taken with Trimble S8 total station, which has a reported angle accuracy of 1" (0.3 mgon). Depending on the distance between the total station and monitoring point/prism measured, the these vertical of deformation accuracy measurements ranged from 0.05-2.0 mm. The manual survey monitored both the ground surface and rail deformation. The ground surface monitoring points were marked with a rebar stake driven approximately 1 m into the ground and the rail points marked with paint on the rail ties. The AMTS monitoring points were marked with reflection prisms located on the rail ties of the mainline tracks and on other infrastructure requiring monitoring.

A large number of surface deformation monitoring points were situated on the rail tracks. Deformation of the rail tracks can be influenced by both temperature and bridging effects. The temperature effect in particular will have an influence on the deformation behavior of the rail tracks, considering there are no expansion joints and long stretches of tracks are welded together. The expansion and contraction of the tracks, as illustrated in Figure 3, coincide with temperature fluctuation throughout the day. The deformation monitoring data presented in Figure 3 is from one AMTS monitoring point located on the mainline track.



Figure 3. AMTS measurement (vertical) vs. temperature.

In addition, long stretches of welded tracks (100+ m) may cause a bridging effect that will also influence the measurement. Figure 4 presents manual survey measurements from both ground and rail monitoring points taken on the same day along transverse profiles located within 10 m of each other. When comparing ground vs. rail measurements, the bridging effect of the rail track is clearly evident, resulting in a difference peak settlement of 2.0 mm.



Figure 4. Comparison of ground and rail measurements.

Proper baselining of survey monitoring points is essential for the successful deployment of a deformation monitoring program. Baseline readings taken prior to the start of construction provide valuable insight into the natural deformation behavior of the ground surface or infrastructure (i.e. without the influence of tunneling). While baseline readings for the AMTS measurements took place as early as 30 days before the start of tunneling, no baseline data was taken for the manual survev measurements. In addition, manual survey measurements can include human error if proper backsighting and controls are not achieved, resulting in systematic shifts. Figure 5 illustrates а systematic shift that occurred between consecutive measurements (1 day apart) while tunneling was not ongoing in the near vicinity of the transverse profile. This, in conjunction with infrequent measurements and the heavy traffic of the rail yard, leads to a high uncertainty in the manual survey data, as discussed further in the following sections.



Figure 5. Example of systematic shift in manual survey data.

3. Deformation Analysis

Example observed ground deformations from manual and AMTS rail monitoring points are presented in Figure 6. The times when each tunnel face passed the closest distance to the monitoring point are indicated by the annotated vertical lines. When comparing the measurement frequency for the manual survey and AMTS, the consequences of the sporadic readings for the manual survey points are clearly evident. For example, the higher frequency measurements for the AMTS readings allows for one to quantify the variation in readings throughout the day due to environmental factors (e.g. temperature), as demonstrated in Figure 3, and the precision of the measurements. In addition, higher frequency measurements allow for the identification of outliers or invalid readings when a single measurement deviates from the mean as well as identifying systematic shifts due to factors such as movement of the prism due to site conditions (e.g. re-ballasting, presence of trains, etc.).



Figure 6. Typical manual survey (a) and AMTS (b) observed rail deformation.

Examination of the manual survey deformation data in Figure 6(a) reveal a precision uncertainty of ± 1 mm as evidenced by the measurements taken during the passage of tunnels YL and A. However, manual survey readings taken well after the passage of tunnel BC vary from 0 to 4 mm (heave), suggesting a precision uncertainty of ± 2 mm. Based on the manual survey readings, essentially zero ground deformation occurred due to tunnels YL and A. Tunnel D, on the other hand, appears to have induced settlement up to 4 mm, shortly followed by ground heaving as result tunnel BC. However, it's not clear if tunnel BC actually caused ground heaving (difficult to achieve). The lack of temporal measurement frequency prevents some unknowns (e.g. systematic shifts, ground heave, temperature effects) from being answered.

The AMTS deformation data in Figure 6(b) reveals a precision uncertainty of ± 1.5 mm throughout the entire duration of the monitoring program. Based on the AMTS readings for this monitoring point, tunnel YL causes little ground deformation, although there appears to be a slight settlement trend as soon as tunnel YL passes. It's not clear if tunnel A causes the settlement that occurred between tunnel YL and A passages. Analysis of the data in relation to the position of the tunnels would perhaps better reveal which tunnel induced the slight settlement. Nearly zero deformation (minimal heave) occurs as tunnel D passes while tunnel BC appears to induce approximately 2 mm of settlement. It warrants mentioning that the AMTS data appears to be very consistent between tunnels A and D, revealing а high repeatability in the measurements.

The higher frequency AMTS measurements allows for a detailed assessment of the ground response as a result of tunneling. The continuous monitoring provides information of paramount importance to establish trends in the ground deformation during tunneling through quantification of the pre-settlement, settlement due to the shield void gap and consolidation settlement. The aforementioned advantages of the high frequency measurements and continuous that monitoring demonstrate the AMTS measurements are much more reliable and useful than the manual survey measurements.

The monitoring program during the project consisted of a high spatial density array of both manual survey and AMTS surface deformation monitoring points. Using a high spatial density of the surface deformation monitoring points allows for detailed assessment of zone of influence due to tunneling. The manual survey monitoring points encompassed an area of 14,000 m² with 380 monitoring points and the AMTS monitoring points encompassed an area of 25,000 m² with 573 monitoring points. These high spatial density arrays proved beneficial for assessing the zone of influence for each of the four tunnels along various sections of the tunnel drive within the variable glacial soil.

The continuous monitoring of the AMTS points provides the opportunity to analyze the settlement trend as the TBM approaches and passes any given monitoring point. Figure 7 presents the change in settlement and 20 period moving average for one AMTS monitoring point as a result of one tunnel (BC). As illustrated by the moving average, very little pre-settlement occurs ahead of the cutterhead as the TBM approaches. Immediately after the cutterhead has passed, a mild settlement of 2 mm occurs before gradually consolidating an additional 1.5 mm by the time the cutterhead is 100 m pass the monitoring point.



Figure 7. Observed settlement in relation to relative position of cutterhead.

The ground behavior indicates that deformation occurred at the crown of the radial shield gap, causing nearly 2 mm of immediate settlement at the surface followed by 1.5 mm of consolidation settlement. After the initial settlement, the rate of settlement was quickly information regarding reduced. This the settlement trend/behavior is extremely valuable to the contractor and TBM operator, especially in highly variable soils, allowing for real-time risk assessment and possible adjustments when needed.

4. Discussion

4.1. Risk Management Aspects

Shallow cover soft ground slurry TBM mining carries with it inherent risks that can manifest ground settlement or heave and impact surface structures. On the East Side Access Queens Bored Tunnels project, the contractor was responsible for limiting the impact to the in service railroad infrastructure throughout the duration of the four tunnel drives. Due to the success and limited surface impact of the first two tunnel drives, the client reevaluated the potential for the addition, removal, and confirmation of certain planned aspects of the final two drives. This included the extension of the B/C Tunnel drive by 430 feet, the removal of the B/C and D tunnel safe havens which would have been extremely difficult to construct due to close proximity of existing railroad the evaluation of the infrastructure. and the instrumentation necessarv for the mining underneath a sensitive railroad signal tower along the D tunnel alignment.

Each of these decisions required a necessary evaluation of risk. This risk was quantified through the use of risk registers and risk matrices developed by the construction management team and shared with key railroad and program management personnel to populate. These documents considered the potential outcomes for and against the changes in the contract. They were evaluated on an individual and overall basis with cost and schedule aspects to develop a risk score which influenced the final decision to be made.

One of the key benefits in evaluating risk in this manner was the sharing of the risk among the parties involved. The risks were clearly identified which encouraged open communication of the key project aspects and engaged all parties in the decision making process. The process was successful with regards to the three aforementioned project changes. The B/C Tunnel alignment underwent an extension of 430 feet, the two planned TBM safe havens were deleted, and a critical railroad signal tower was heavily instrumented in anticipation of the close proximity mining underneath it. Each of these risk based decision culminated in a positive impact to the CQ031 contract success.

4.2. Recommendations for Future Works

Considering the lessons learned from both the successes and issues with the East Side Access Queens bored tunnels monitoring program, recommendations for potential improvements to risk-reduction through monitoring are as follows:

- When possible, use automated surveys (e.g. AMTS) with high frequency measurements to capture settlement trends, precisions, systematic shifts, etc.
- Deploy a high density array of monitoring points to determine the zone of influence due to tunneling.
- Obtain as much baseline data as possible to identify potential issues with the measurements such as drift, poor line of sight, natural oscillations in ground deformation and seasonal effects.
- Independently verify measurements using other remote sensing techniques (e.g. Lidar, InSAR, etc).
- When site conditions prohibit automated and continuous surveys, extensive measures should be taken to maintain good control when conducting manual survey measurements (e.g. multiple control points, higher frequency measurements, well-protected stakes and markers).

5. Conclusions

Risk-reduction through monitoring of ground surface deformation was performed using both traditional manual survey and AMTS. The AMTS monitoring proved to have a clear advantage over manual survey as the high measurement frequency, real-time monitoring provides invaluable information that sporadic manual survey measurements do not provide such as identifying poor measurements, precisions, systematic shifts and settlement trends. However, it is not always feasible to deploy an automated survey. This was the case for the rail yard monitoring points as high train

traffic would interfere with the automated, continuous monitoring.

While the monitoring program conducted at the East Side Access Queens bored tunnels project was considered to be very successful, there were some issues that warrant discussion. Due to the activity in the rail yard, specifically train activity and re-ballasting of the tracks, a number of surface deformation points were affected and often resulted in false alarms with the manual survey data. In addition, the rebar stakes used to mark the ground surface monitoring points were often disturbed by the high traffic within the rail yard which also resulted in occasional false alarms. These issues highlight the challenge of conducting real-time monitoring in heavy traffic zones such as an active rail yard and exemplify the need for careful control of monitoring programs deployed in urban, high traffic environments.

References

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