Case Study: Automatic Reflector-less Surface Deformation Monitoring of a 21-lane Highway during SEM Tunneling Construction

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ABSTRACT
In underground construction, geotechnical monitoring allows the instant evaluation of the performance of the work and contributes to maintaining public safety in the project's environment. Automatic Motorized Total Stations (AMTS) provide automatic, high precision and near-real time monitoring of the ground and of surrounding structures. This paper introduces AMTS in reflector-less mode, to monitor ground deformation during a Sequential Excavation Method (SEM) tunneling project in Canada. The Highway 401 and 409 Rail Tunnels project requires continuous near real-time monitoring of nearly 500 points across a 21-lane highway with no interruption of traffic. This paper explains the workflow of RTS in this context. The authors focus on the specifics of the design of this unique reflector-less monitoring program and on challenges addressed during its implementation and maintenance. The paper is aimed to confirm the relevance of RTS in reflector-less mode for tunneling activities in urban areas.

RÉSUMÉ
Les travaux d'infrastructures souterraines impliquent la mise en œuvre de programmes sophistiqués d'auscultation du sol et des structures impactées. Ces systèmes incluent souvent des Stations Totales Robotisées (RTS) car elles fournissent des données de haute précision en temps quasi-réel sur les mouvements et les déformations. Cette publication présente les RTS utilisées en mode sans contact sur le projet de la traversée de l'autoroute Hwy401 (Ontario). L'autoroute la plus fréquentée d'Amérique du Nord, avec 21 voies contiguës traversées par un tunnel creusé en méthode séquentielle (SEM), doit être surveillée en continu avec 500 points sur la chaussée, sans perturbation du trafic. Les auteurs présentent les détails techniques du design du système d'auscultation, avec une attention particulière sur les défis liés à la taille du projet et aux spécifications draconiennes imposées par les parties impliquées. A ce jour, les RTS ont démontré leur parfaite performance pour assurer la sécurité des utilisateurs.

1 PROJECT BACKGROUND

The Highway 401 and 409 Rail Tunnels is a Metrolinx GO Expansion project between Kipling Avenue and Islington Avenue along the Kitchener Corridor in the City of Toronto, Ontario. The project is being undertaken by Toronto Tunnel Partners (TTP), a joint venture between Strabag Inc. and EllisDon Civil Ltd. under a contract to Infrastructure Ontario and Metrolinx. The purpose of the project is the construction of new twin tunnels in an effort to establish future all-day, two-way, more frequent GO Transit rail service on the Kitchener Corridor. The proposed tunnels are to be constructed adjacent to an existing rail tunnel (constructed in 1965), with three (3) live rails. The tunnel is mined beneath twenty-one (21) lanes of live highway, 401 and 409, North America's busiest highway corridor. The two (2) tunnels are each approximately 180m long and are being constructed via Sequential Excavation Method (SEM) with a minimal overburden. The execution of tunnel construction must ensure the unimpeded operation of both the highway and rail corridors. To ensure the safety of the travelling public on the highway and rail corridors, stringent limits of movement have been prescribed. Considering the above, the project required a highly complex monitoring system; Sixense Solution Canada Ltd was retained by Toronto Tunnel Partners (TTP), to provide instrumentation and monitoring services for the duration of the project.

1.1 Construction Method

Prior to excavation of the twin tunnels, a full pipe roof pre-support canopy is established. The pipe roof is constructed via 813mm steel pipe. Pipes are installed using Auger Boring Technology (Jack & Bore). A drop shaft is constructed within an existing highway median to ensure a full pipe roof canopy can be constructed, considering existing tunnel structures. The pipe canopy roof is pushed into place using a 200-ton jacking frame; pipe length varies dependent on location, 4m, 6m and 12m long pipes are available. Ground improvement measures are conducted as required.

The approximately 8.5m wide, 10m tall tunnel cross section excavation has been divided into a top and bottom heading. Top heading excavated in sequential advancements (strokes) and exposed soil is immediately sealed with 5 cm shotcrete initial support. The initial support consists of lattice girders, mesh reinforcement and 25 cm of shotcrete. The bottom heading will be excavated in sequential advancements. Top and bottom headings are offset to limit movement.

1.2 Instrumentation Requirement

Due to the high sensitivity of the project, the complexity of the construction sequence and its close vicinity to critical infrastructures such as the highways and existing railway tunnel, a comprehensive geotechnical monitoring plan was implemented to monitor highway surface and sub-surface settlement, ground and adjacent structures deformation, pore water pressure as well as construction induced vibration and noise. The entire monitoring period includes a 6-month pre-construction baseline, an approximately 2.5-year construction phase, and a final 12 months post-construction close-out phase. Surface monitoring is the most challenging part, which includes 21 lanes of two major highways (lanes, shoulders and median), as well a section of highway ramp retaining wall. It is achieved mainly through using an automatic reflector-less monitoring system, whose design and implementation will be introduced in this paper.

Figure 1. Photo of construction taken from East Portal showing the pipe canopy roofs have been installed for both tunnels.

2 AMTS FOR DEFORMATION MONITORING

Ground deformation is one of the most common monitoring items for construction projects such as tunneling or deep excavation in urban areas. In modern instrumentation and monitoring practice, AMTS becomes a standard tool for automatic, near real-time displacement monitoring (Ning, et al. 2019).

2.1 Principle and Workflow

The basic principle of AMTS deformation monitoring (see Figure 2) is using an AMTS to continuously track the position of monitoring reflectors through its automatic target recognition (ATR) function and compare consecutive measurements. In each cycle of measurements, the AMTS sights both a certain number of reference (or back sight) points whose position are known (fixed), and monitoring points whose positions are subject to change. These reference points are located in stable zones outside the monitored zone so the instant position of the AMTS can be accurately determined by least squares adjustment, even though in most of the cases the AMTS itself is inside the monitored zone (to stay close to the monitoring points to acquire better line-of-sights and increase measurement accuracy). Once the AMTS position is determined and updated, the positions of the monitoring points are determined by trigonometry usually expressed in Cartesian coordinates (X/Y/Z). With an adequate number of reference points providing computational redundancy for least squares adjustment, potential unexpected movements of any particular reference points can be detected so the moved or damaged reference points can be discarded and replaced.

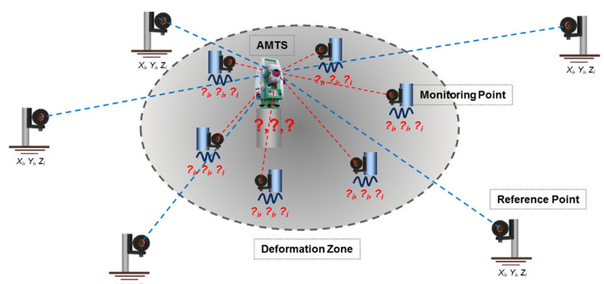

Figure 2. principle of displacement monitoring using AMTS.

2.2 AMTS in Reflector-less Mode

AMTS is primarily operated in reflector mode. However, the fact that the prisms need to be attached to the surface of monitored objects often time creates a constraint for its implementation, e.g. the right of access to install prisms in either private or public areas might not be granted. When the prisms are used to monitor the road settlement, traffic closure is required during the installation of prisms. Prisms can get dirty quickly or damaged by vehicles, which requires frequent maintenances. The safety of operators during installation and maintenance near heavy traffic is also a concern (Ning, et al. 2019).

Due to these demands, the capability of carrying out AMTS reflector-less measurements has been developed and reportedly applied in tunnel projects since 2005 (ITAtech, 2015). The reflector-less technique uses electro-magnetic waves (as the standard AMTS does) but measures directly an object's surface having appropriate reflectivity. Unlike the standard AMTS, for which the ATR is guiding the AMTS to shoot the same target, reflector-less measurements approximate such repetition by fixing the horizontal and vertical angle of the AMTS. An immediate and obvious issue is that if the measurement surface deforms (e.g. settlement), the AMTS is not shooting the same point. This effect therefore restricts the reflector-less method to only deliver 1D deformation but is still suitable for settlement monitoring. Since the need for a physical reflector is eliminated, a much larger number of reflector-less monitoring points can be defined for the target area (theoretically, it is only limited by the required monitoring frequency). With the current Electronic Distance Meter (EDM) technology, mm-level repeatability can be achieved and proven in many projects when the measuring distance is within 250ft and the incidence angle (the angle between the line-of-sight and the measured surface) is greater than 1:10. When the point density is high enough, a deformation surface can be generated through interpolation as shown in Figure 3.

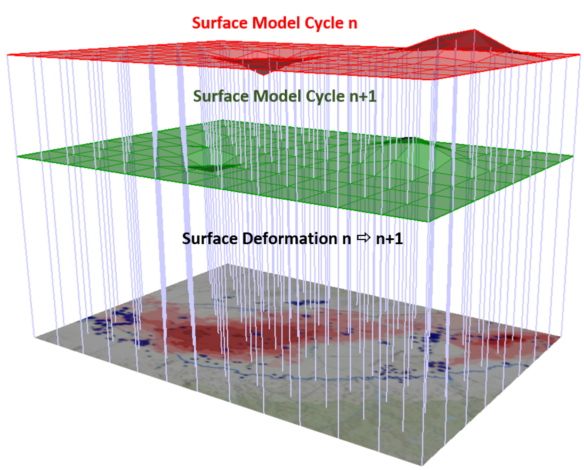

Figure 3. Deformation surface generated from high density AMTS reflector-less monitoring points

3 SURFACE SETTLEMENT MONITORING REQUIREMENTS OF HWY 401 PROJECT

During the design phase, both analytical and numerical studies have been conducted to estimate the ground deformation caused by the tunneling construction, thus the Project Zone of Influence (PZOI) was defined. The critical infrastructures within the PZOI that require surface settlement monitoring are: 21 lanes of two major highways (lanes, shoulders and median) as well as a section of the retaining wall of the highway ramp. The affected highway section being one of the busiest traffic corridors for the city, a key strategy taken into consideration for monitoring is to minimize interruptions of existing highway traffic as well as to minimize manual readings in areas of heavy traffic that can put personnel in unsafe conditions.

The required density of the surface monitoring points on highway lanes is 2.75 meter by 2.75 meter. A 10-15 minutes reporting interval was desired within the active construction zone (ACZ) during tunnel excavation. Other requirements for the surface settlement monitoring include +/- 2 mm measurement repeatability and near real-time data transmission to an Automated Data Acquisition and Management System (ADAMS).

4 SYSTEM DESIGN AND IMPLEMENTATION

4.1 Instrument Selection

By analyzing the project monitoring requirements, particularly the goal to minimize interruptions to the highway traffic, a non-invasive remote sensing technique was preferred. There are several such techniques suitable for ground or structural deformation monitoring: AMTS, laser scanning (Lidar) and radar satellite interferometry (InSAR) (Stark, et al 2020). Although all the three technologies can achieve high spatial density and high precision measurements to satisfy the project requirements, AMTS has the following advantages:

- Much lower cost (in both hardware and post processing)
- Simpler and faster data processing (point cloud processing for laser scanning requires heavy and relatively time-consuming computation. For InSAR, the shortest monitoring frequency is in days limited by the satellite revisiting period)
- Can operate in both reflector-less mode for highway surface monitoring and in reflector mode for highway ramp retaining walls, curb and median monitoring.

4.2 Optimizing Monitoring Zone and AMTS Configuration

Due to the required high monitoring frequency and spatial density of monitoring points, the PZOI is further refined to a smaller Monitoring Zone of Influence (MZOI) which only extends from the north wall of the existing rail tunnel to the north end of the excavation zone of the new tunnels across the entire length of the proposed tunnels. Within the MZOI, a 2.75m by 2.75m monitoring grid defines a total number of 447 reflector-less points across 21 lanes of Hwy401/409 (as shown in Figure 4).

Taking into consideration the normal AMTS operating time and an estimated traffic impact of 40% chance retry (a 2nd measurement when the 1st fails), it is estimated to take 1 hour for an AMTS to measure about 100-120 points, which is approximately ¼ of the entire MZOI. A dynamic AMTS monitoring scheme is defined in accordance with the construction activities to maximize the system's efficiency while minimize the hardware cost.

- Four AMTS were installed during baseline monitoring prior to the construction which delivered an averaged 60 minutes cycle time.
- Four additional AMTS were added during construction phase to form 4 twin-AMTS

monitoring stations: when there is no active construction, the cycle time is reduced by half to approximately 30 minutes.

- When the ACZ is within the monitoring area, one AMTS focuses on the 11m by 11m ACZ which results in a fast 5-10 minutes cycle time while the 2nd AMTS covers the remaining monitoring points (Figure 4)

Through the AMTS piloting software, AMTS can be conveniently programmed to follow the ACZ as the installation of the pre-support and excavation operation progress across the entire monitoring zone.

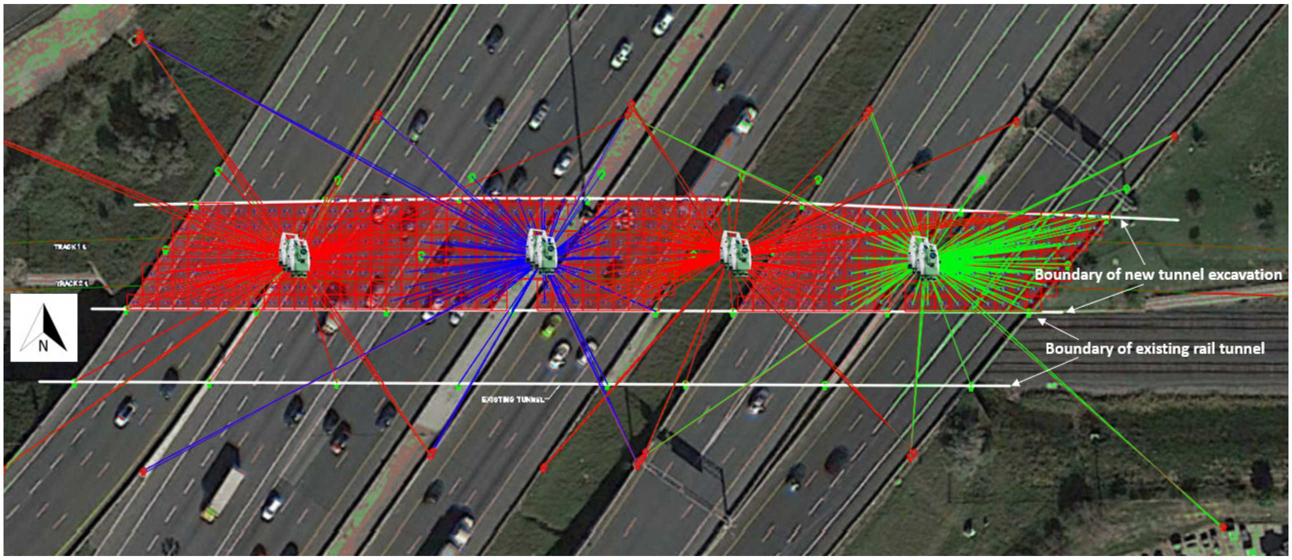

Figure 4. Reflector-less monitoring grid in the Monitoring Zone of Influence

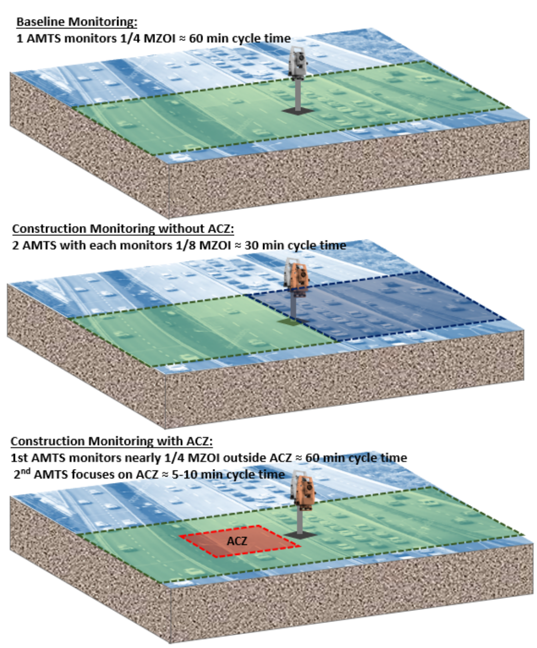

Figure 5. Construction phase-based AMTS monitoring scheme

4.3 Filed Implementation

Due to the site constraints for AMTS tower foundation installation, the 1st and the 3rd pair of AMTS had to be moved slightly to the north of the centerline of the excavation. The heights of the AMTS mast are determined to satisfy the incident angle requirement. (defined in 2.2). Two 6-meter and two 9-meter masts were designed by a professional structure engineer and installed by the contractor.

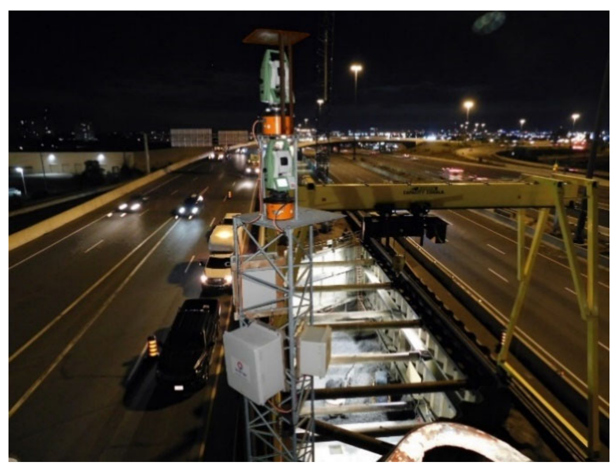
Figure 6. Monitoring tower with twin-AMTS.

The top of the AMTS mast is designed to accommodate two AMTS. The first four AMTS were installed in November 2018 for baseline monitoring and the additional four AMTS were added 6 months later on top of the existing ones. Figure 6 shows one of the twin-AMTS monitoring tower covering the middle lanes of the highway.

Figure 8. Four AMTS towers observed from *Google Earth* street view

5 MONITORING DATA PREVIEW

At the time of writing, the project is still on going and the detailed analysis of monitoring data will be discussed in a separated publication. Figure 8 shows the actual locations of reflector-less points captured by the 8 AMTS displayed on project's ADAMS GIS platform. Some of the points are slightly offset from the grid center due to line-of-sight obstruction.

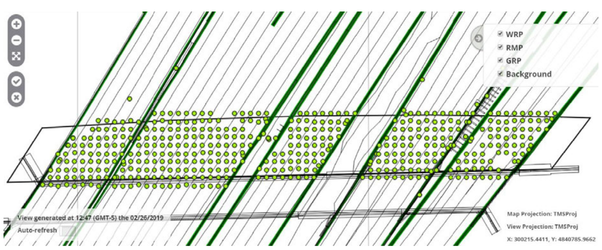

Figure 8. Reflector-less monitoring points shown in the ADAMS GIS Interface

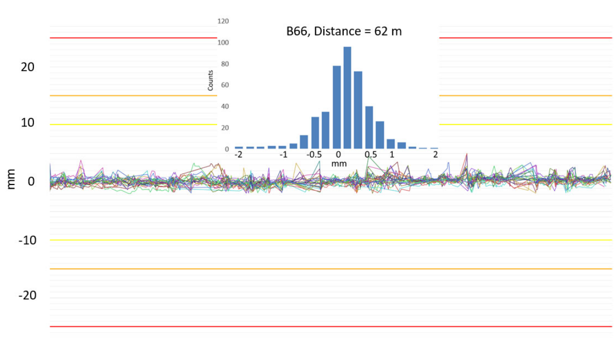

Figure 9. 30-day reflector-less settlement monitoring data during baseline monitoring.

Figure 9 shows a 30-day time-series graph of all the settlement monitoring points in the second row (the 2nd row from the top in Figure 8). The measuring distance of these points range from 20 to 62 meters. Within this distance range, the precision of the measurement is consistent with an averaged standard deviation of 0.59 mm.

CONCLUSION

This case study describes the design and implementation of an automatic road settlement monitoring system based on reflector-less AMTS technique, as well as explains the principles of using AMTS for displacement monitoring.

The study shows AMTS reflector-less is an economical and effective solution compared to other state-of-the-practice remote sensing techniques. It achieves high precision and high spatial density measurements while minimizes the interruptions to the traffic and the personnel exposure to traffic. It provides sub-millimetre precision (1 standard deviation) without showing a degradation of data quality while measuring distances up to 60 meters. The measuring distance can be further extended on many other applications, should the precision requirement be less stringent.

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