The effect of TBM tunneling on the surface and underground deformations under Montreal-Trudeau international airport (YUL) runway

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ABSTRACT: The Réseau Express Métropolitan (REM) is a light rail system that spans 67 km and will link the Pierre-Elliot-Trudeau International Airport to the greater Montreal area. As part of the system, a 3 km tunnel starting at the Marie-Curie station is being built by a TBM machine with a diameter of 7.37 m to join the airport station. The tunnel alignment passes under airport runway 06L/24R. To estimate the effects of TBM tunneling on surface subsidence under runway 06L/24R, a 2-D numerical analysis was conducted using the FLAC-2D code. Moreover, to monitor the surface and ground movements by TBM tunneling, geotechnical instruments as well as radar imagery InSAR system were installed along the tunnel alignment. The numerical modelling results show that the induced ground surface settlements for runway 06L/24R caused by TBM tunneling is negligible and the results obtained from geotechnical instruments were validated against the numerical analysis findings.

Keywords: TBM tunneling, numerical analysis, geotechnical instruments, surface subsidence, underground movement.

1 INTRODUCTION

The airport tunnel includes a 3 km tunnel that connects the Marie-Curie station to the Montreal Airport station. The tunnel is excavated with an EPB TBM shield machine with a diameter of 7.37 m. The 6+1 segmental lining system, as a support system for the tunnel, was installed during the tunnel excavation. The tunnel alignment passes under airport property and runway 06L/24R. The terrain above the crown amounts to about 30 m including up to 16 m of rock and 14 m or more of soil. The behavior of the surface and underground movements under the runway of the Montreal airport was modelled prior to construction and monitored by the installed geotechnical instruments and InSAR system during TBM tunneling.

2 GEOLOGY AND WATER GROUND CONDITION

Under the Montreal-Trudeau international airport's runway 06L/24R, TBM tunnel advancement is carried out through a competent bedrock which is composed of limestones with interbeds of shale under the sedimentary cover with 2 m of fractured rock and 14 m of heterogeneous soil up to the surface (Figure 1).

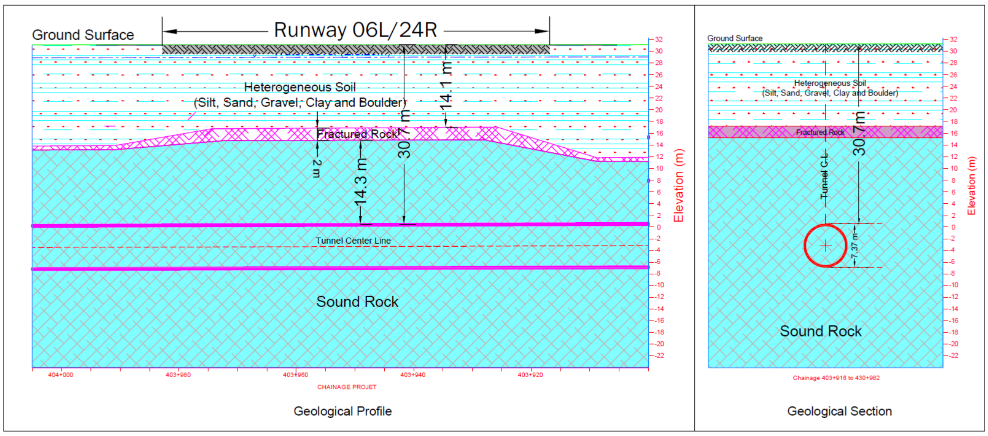

Figure 1. Geological profile and section under runway 06L/24R.

According to the conducted tunnel face mappings under runway 06L/24R, the rock mass quality was classified as good rock and very good rock (Class II and I) having an RMR (Rock Mass Rating) value between 69 to 81. In addition, during the tunnel face inspection, no water ingress was detected at the tunnel face. The average groundwater elevation measured in the runway 06L/24R area is 3 m below the ground surface.

3 MONITORING THE SURFACE AND GROUND MOVEMENTS BY TBM TUNNELING UNDER THE RUNWAY 06L/24R

To monitor any impact of TBM tunnelling on ground behavior during the excavation by TBM in a live manner, 4 vertical inclinometers, 2 extensometers, and 2 inclined inclinometers were installed along the tunnel alignment (Figure 2). Also, a radar imagery InSAR system was performed every alternating 4 and 7 days along the tunnel alignment during TBM tunneling to monitor the ground surface movements.

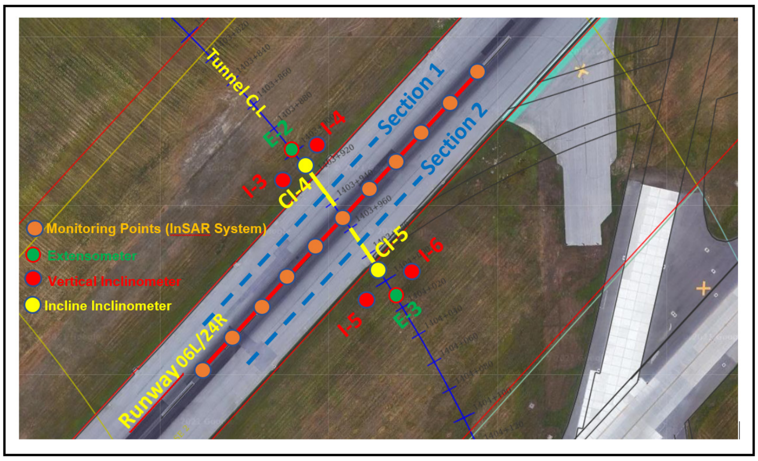

Figure 2. Plan view of the geotechnical instrumentation and InSAR monitoring points near the runway 06L/24R.

3.1 *Surface Settlement Assessment*

To monitor the ground surface behavior of the runway 06L/24R, 11 monitoring points, having a spacing of 10 m, were monitored by the InSAR system during TBM tunneling. The results of the InSAR system show that the behavior of the area in runway 06L/24R was characterized by a mild displacement (less than 5 mm). It should be mentioned that the precision of InSAR system is 5 mm. Thus, the InSAR results shows that there was no significant settlement following the data obtained for runway 06L/24R due to TBM tunneling. Figure 3 shows the ground surface deformations of the runway which were measured by the InSAR system.

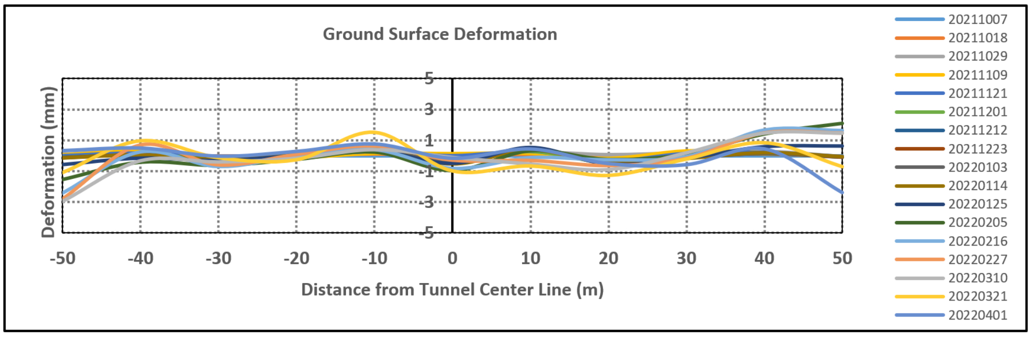

Figure 3. Ground surface deformation for runway 06L/24R by InSAR.

3.2 *Underground Movement Assessment*

The underground behavior due to TBM excavation in the runway area was analyzed by monitoring the 4 vertical inclinometers (I-3, I-4, I-5, and I-6) and 2 extensometers (E-2 and E-3) and 2 inclined inclinometers (CI-4 and CI-5) which were installed under the runway 06L/24R. During the tunnel excavation under the runway, a maximum local displacement of 14.81 mm was recorded in the TBM influence zone at the tunnel horizon by vertical inclinometer I-3. The observed movement of 14.81 mm occurred in parallel to the tunnel alignment (B direction). But on the opposite side (A direction), which is the main direction for monitoring tunnel convergency (this direction is perpendicular to the tunnel alignment) a maximum displacement of 6.4 mm was recorded by inclinometer I-3 (Figure 4). Whereas the recorded movements of the Inclinometers I-4, I-5, and I-6 in both directions A and B are less than 6 mm. Moreover, the first and second threshold values for inclinometers are 6 mm and 9 mm respectively and they shown in Figure 4 by orange and red dots lines.

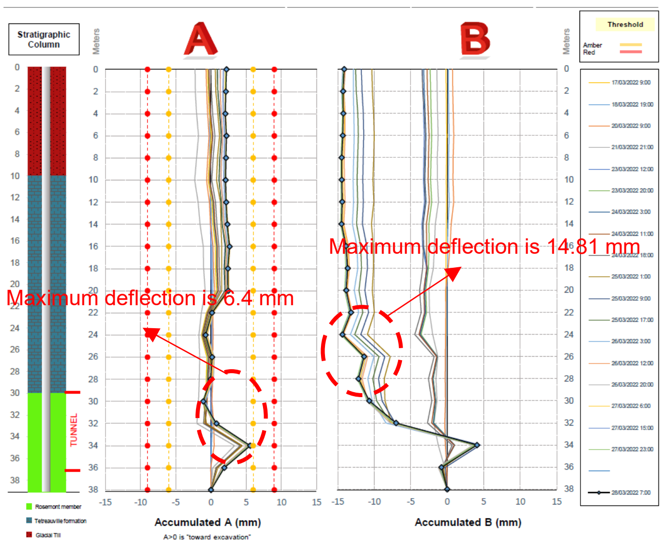

Figure 4: Displacement profile recorded by Inclinometer I-3.

Furthermore, TBM tunneling influence on the surrounding media starts from 20 m before TBM reaches the instruments and finishes 20 m further away in the tunnel influence zone (Figure 5).

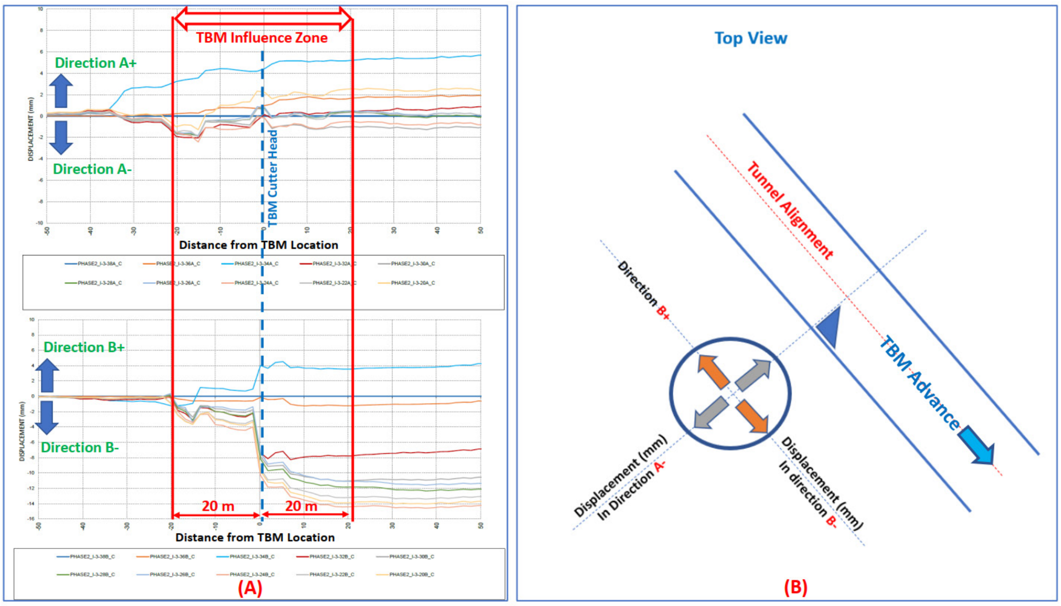

Figure 5: (A) Deformation profile recorded by Inclinometer I-3 in directions A+, A-, B+, B as a function of TBM advance (B) The location of inclinometer I-3 to the tunnel alignment.

In addition, no movements were recorded by extensometers E-2 and E-3 in the upper layers of the top of the tunnel during TBM tunneling under the runway 06L/24R.

4 GROUND SETTLEMENT ASSESSMENT OF RUNWAY 06L/24R

To estimate the effects of TBM tunneling on surface subsidence under runway 06L/24R, two typical cross-sections along the profile, with different overburden were analyzed using the FLAC-2D software. In the first cross-section (section 1), the tunnel was covered by 5.7 m of sound rock, 11 m of the fractured rock layer, and 14 m of heterogeneous soil up to the surface. The second cross-section (section 2) analyzed involved a better geotechnical condition for tunneling than section 1. In section 2 the crown of the tunnel has 14.7 m of sound rock cover, 2 m of fractured rock, and 14 m of heterogenous soil up to the surface. The two analyzed sections are illustrated in Figure 2.

4.1 Numerical Analysis

To evaluate the induced settlement on the ground surface caused by the passage of the TBM under runway 06L/24R, the FLAC 2-D (Ver 8.1) code of ITASCA Consulting Inc. (Itasca 2021) was used for numerical analysis (sections 1 and 2). The assumptions of the 2-D numerical analysis to simulate TBM tunnelling under the runway 06L/24R are as below;

- Displacements in the excavation face are zero (Tunnel face is stable)
- TBM tunnel excavation is simulated in one sequence
- The support system for the tunnel (segments) is installed immediately after the tunnel excavation
- Soil and rock layers are horizontal
- The material condition is homogeneous and isotropic (the heterogeneous soil has been modelled conservatively as homogeneous)
- Discontinuities within and between the rock layers have not been considered directly
- Plane-strain analysis conditions
- Dynamic loads due to the aircraft impact during TBM excavation was not considered

4.2 Design Parameters

The design parameters of soil and rock in numerical analysis is mainly estimated from the results of the rock strength test on samples obtained from four boreholes CI-4, E-2, CI-5, and E-3, and also the geotechnical design parameters report for airport tunnel (Khosravi et al. 2019 and Soudkhah et al. 2021). The employed design parameters used in the numerical models for layers of soil and rock are presented in Table 1. In addition, to determine rock mass parameters, the RocLab software (Rocscience) was used. Furthermore, the RMR values were determined by rock mapping during the TBM construction. However, the design parameters (including GSI) were assumed in design phase (before construction). Given that the design assumptions were more conservative, we are already at the safe side.

Table 1. Soil and rock properties.

Parameter		Soil	Fractured rock	Sound rock
Density	[Kg/m^3]	1800	2400	2600
Deformation Modulus (E)	[MPa]	15	4170	4170
Poisson's ratio	[-]	0.25	0.13	0.13
Cohesion	[KPa]	0	-	-
Friction angle	[°]	30	-	-
Tensile Strength	[MPa]	0	0	0
Dilation	[°]	0	-	-
UCS	[MPa]	-	25	25
GSI	[-]	-	25	50
mi	[-]	-	8	10
D	[-]	-	0	0

4.3 Ground Surface Settlement Profile

The modelled ground surface settlement profiles for sections 1 and 2 are illustrated in Figure 6. According to Figure 6, the maximum settlement for sections 1 and 2 are 0.34 mm and 0.2 mm respectively which is negligible in terms of practical geotechnical design. Furthermore, the first and second threshold of surface displacements under runway 06L/24R of 6 mm and 9 mm respectively cited in the owner's project requirements and as shown on figure 6 demonstrates that the maximum settlements assessed are well under the allowable thresholds.

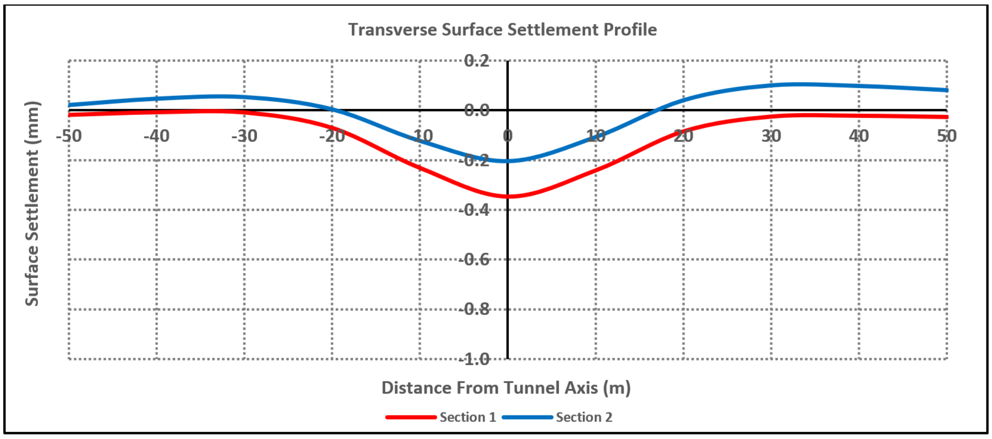

Figure 6. Ground surface settlement profile for runway 06L/24R by numerical modeling.

5 VALIDATION OF 2D NUMERICAL MODELING

For validation of 2D numerical analysis, the results of the InSAR system were compared by the maximum displacement computed by numerical modeling. The results of the InSAR system illustrated that the maximum measured deformations due to TBM tunneling under the runway are less than 5 mm whereas the maximum displacements calculated by numerical simulation is 0.34 mm. Therefore, the values of induced ground surface settlements for runway 06L/24R due to TBM excavation is negligible in terms of geotechnical design, and the geotechnical instrumentation results are in harmony with the conducted numerical analysis.

6 CONCLUSION

The results of the conducted numerical modelling exercise and tunneling monitoring work led to the following concluding remarks:

- The 2D numerical modeling shows that the induced ground surface settlements for runway 06L/24R caused by TBM tunneling would reach a maximum of 0.34 mm which is negligible in terms of geotechnical precision.
- The outcome of the InSAR system illustrates that the behavior of the runway area is stable with a mild displacement on average less than 5 mm during TBM tunneling.
- A maximum of 14.81 mm local horizontal movement in the TBM influence zone was recorded at the tunnel depth and in parallel to the tunnel alignment. While, on the opposite side (perpendicular to the tunnel alignment), which is the main direction for monitoring the tunnel convergency, a maximum movement of 6.4 mm was recorded.
- TBM tunneling influence on surrounded media starts from 20 m before TBM reaches the instruments and finished 20 m further away in the tunnel influence zone.
- There is no movement recorded by extensometers in the upper layers of the top of the tunnel during TBM tunneling under the runway 06L/24R.

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