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TITLE: **Deep Excavation Support – Shangri-La – Toronto**

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Abstract

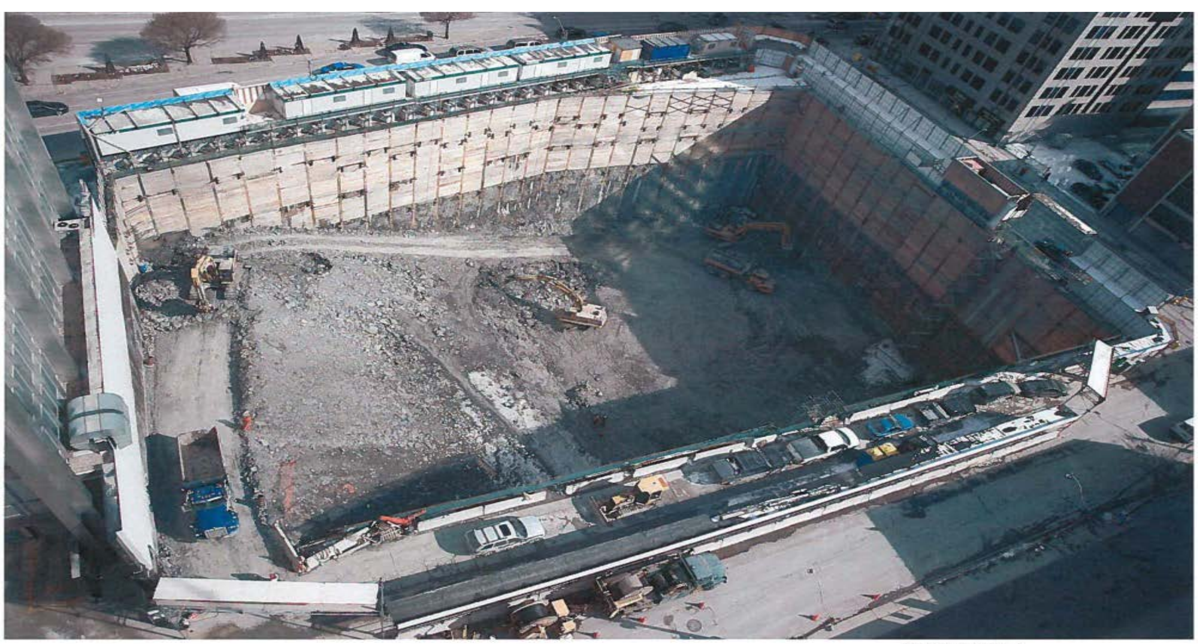
The Shangri-La hotel and luxury condominium tower, recently opened on University Avenue in downtown Toronto, required eight levels of underground structure, four extending into the shale bedrock.

Isherwood Geostructural Engineers was retained in 2007 by Anchor Shoring Limited to provide an alternative design-build solution to better address serious foundation risks. The site, bounded on three sides by City streets, abuts an existing 1957 14-storey building with five underground levels to the north. Sitting on the rock surface along the east perimeter under University Avenue runs the existing Toronto Transit Commission's University Subway Line built by cut-and-cover in the 1950's and which was believed to lie very near the property boundary at the southeast corner of the site.

The bedrock under Toronto is known to contain very high locked-in horizontal stresses, much higher than can be resisted by shoring techniques, which result in inevitable wall movement when excavating deep into the rock. The strategy adopted to control the risk to the Subway, adjacent building, and major utilities is described in the paper, along with the comprehensive monitoring of movements, and their comparison to predictions.

The Project

The 66-storey Shangri-La hotel and luxury condominium tower, recently constructed on University Avenue in downtown Toronto, houses 222 hotel rooms in floors 1-17; 287 residences on floors 18-49; and private estates including two 2-storey penthouses on floors 50-66. These comprise 873,000 square feet of development.



SHANGRI-LA
FEB. 24, 2009
LOOKING SOUTHEAST

Figure 1: Aerial View Shangri-La

Eight levels of underground basement are required to provide parking and other amenities, the lower four extending into the shale bedrock.

The tower is a Toronto landmark, visible down the length of the boulevard-style University Avenue from Queen's Park (the seat of Ontario's Legislature), and is located across the road from the new Four Season's Opera House. The site, bounded by City streets on three sides (Simcoe Street on the west, Adelaide Street on the south and University Avenue on the east), shares the block with an existing 14-storey building (200 University) with five underground levels built in 1957-60. Along the east perimeter, and seated on the rock surface under University Avenue, runs the existing Toronto Transit Commission's University Subway Line with running track in a triple-box structure built by cut-and-cover in the 1950's. This was indicated to lie only 2.5 m from the property boundary at the southeast corner of the site, widening to some 15 m at the northeast corner (see Figures 1 and 2).

Excavation Support Challenges

Isherwood Geostructural Engineers (Isherwood) was retained in 2007 by Anchor Shoring and Caissons Ltd. (Anchor) to provide an alternative design-build solution for their Shoring Proposal, with a mandate to better address the perceived serious risks, particularly to the Toronto Transit Commission (TTC) Subway:

Bracing system

Standard soldier pile and lagging shoring, braced by two levels of rock anchor tiebacks was proposed to retain the overburden soils at the streets. This shoring penetrated and supported the upper weathered rock, but the rock face below was considered self-supporting.

Along the east boundary, where the existing subway obstructed use of normal rock anchors, Isherwood proposed substituting soil anchors (generally two levels) in place of the tender drawings' internal bracing, utilizing the space

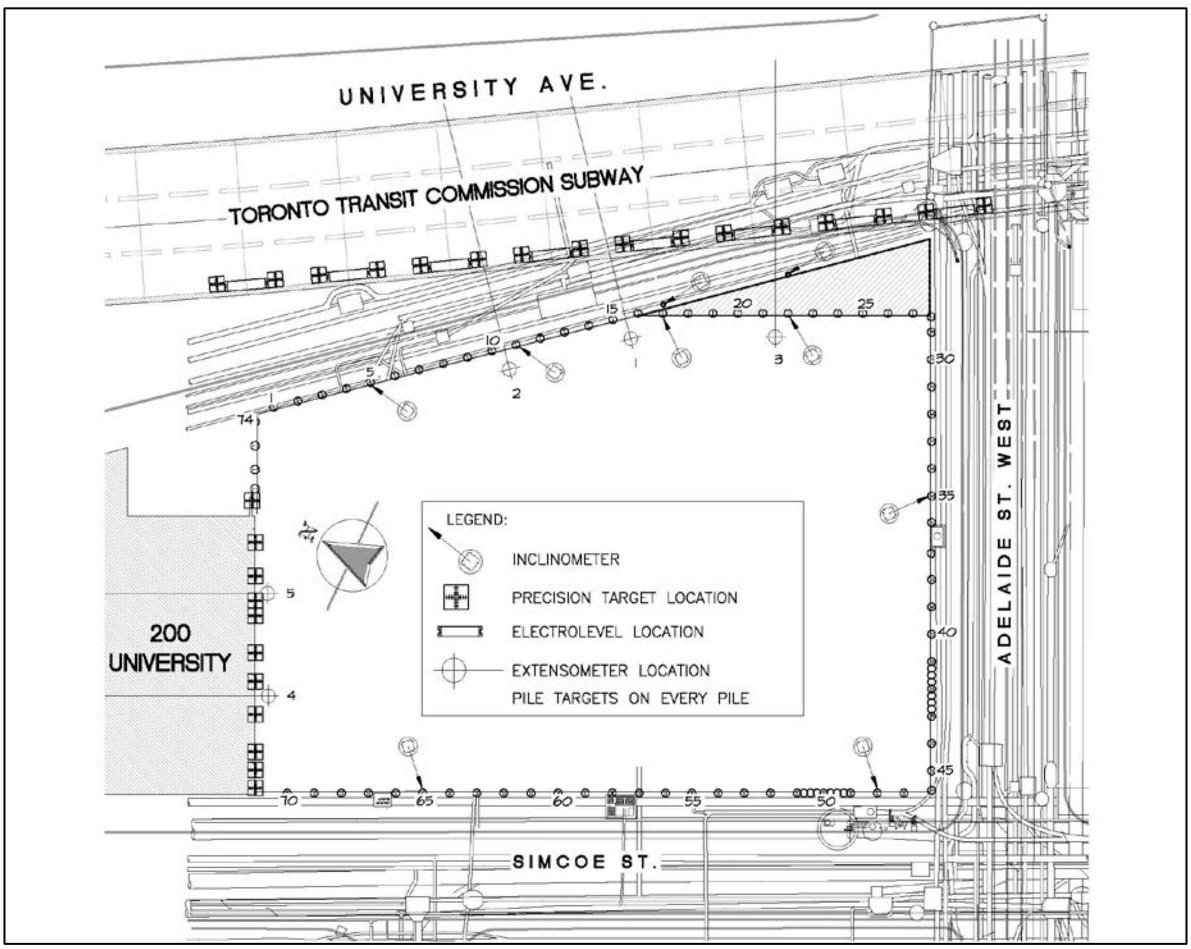


Figure 2: Shoring Layout and Monitoring Plan

between the excavation and subway where adequate, otherwise threading them between the roof of the subway and under existing street utilities to anchor in the subway fill (see Figure 3).

Rock movements

The bedrock under Toronto is known to contain very high locked-in horizontal stresses (Reference 1). The stresses are higher than can be resisted by shoring techniques and result in inevitable wall movement when excavating deep into the rock. The TTC box structures are sensitive to movement, particularly at the construction joints, which are typically spaced 40 ft (12. 2 m) apart. The TTC enforces very strict alert levels for such movements because of potential disruption of service. It appeared from the tender drawings that one of these joints may be located very near the site's critical south west corner where differential rock movement along existing vertical fissures was expected to be at a maximum.

Isherwood's recommendation was that the owner be asked to give up space to allow relocating the basement wall further away from the critical corner. It was finally agreed to abandon all eight levels of basement in a triangular area measuring 9 m x 35 m and thus bring the closest approach to the subway away from the south east corner and nearer to the centre of the wall, providing a uniform movement pattern along the whole east wall (see Figure 2).

Soil Conditions

The proposed excavation was to be 26 m (85ft) deep. The surface of the shale bedrock is relatively flat at about 13 m (43 ft) below ground level. The site had a history of earlier buildings so there were various depths of man-made fill and existing foundations. The natural over-burden consists of dense clayey silts of the Sunnybrook Till, under-lain by the inter-layered sands, silts and clays of the Don Beds, and hard clayey silt of the York Formation over the bedrock. Historically the Don Beds were well-known for providing wet ground in three- and four-basement excavations, but such projects have since effectively drained the main flow in much of the downtown area.

The bedrock of the Georgian Bay Formation is comprised of shale containing inter-beds of calcareous shale, limestone and calcareous sandstone. The shale exhibits very pronounced horizontal jointing, but also contains vertical joints that become visible as the horizontal stresses are relieved during excavation. These are often continuous for many metres both vertically and horizontally. Experience indicates that these joints are more prevalent in an east-west orientation. The rock provides a sound and reliable foundation with typical allowable bearing values of 25 tons/sf (2.5 MPa) for footings and 75 tons/sf (7.5 MPa) for drilled shafts.

A Few Surprises

After award, Isherwood approached all private and public authorities to obtain as-built drawings of adjacent structures and utilities.

1. At a meeting with TTC, Isherwood learned that TTC did not know within 1 or 2 m where the subway was in the curved portion adjacent to the site, and that a survey of the tunnel would be required. Isherwood had information in its archives from work undertaken at the two adjacent stations north and south, and was retained to locate the structure by survey in the tunnels between these stations. This type of work can only be done during a power cut, which, when required, is scheduled for the early hours of Sunday mornings (1 am-6 am). At the same time crews were able to install remote-reading instruments in the tunnels bordering the site for accurately determining joint movement. TTC could provide no information on construction records or on any temporary shoring used. Isherwood assumed this consisted of soldier pile and lagging at 8 ft centres braced by temporary horizontal struts. The tunnel survey revealed that the structure was almost 1 m (3 ft) nearer to the property, with offsets of 1.78 m (6 ft) and 14.08 m (46 ft) at southeast and northeast corners, and that the nearest joint was some 9 m (30 ft) north of the critical corner. With the revised excavation footprint, the smallest clearance to the subway became 7.30 m (24 ft).

2. A visit to inspect 200 University revealed that the basements were built in a half-step scissor arrangement along the building's south wall rather than horizontally as shown on the tender drawings. Isherwood was able to obtain copies of the structural drawings. Again, no construction details were available, but Isherwood assumed there had been existing buildings on the Shangri-La site

which likely had been underpinned by concrete panels to the rock. This proved to be the case.

3. Drawings obtained from Toronto's archives revealed that a 2 m diameter sanitary sewer along Simcoe Street, shown on the tender drawings at shallow depth, was actually tunneled in the rock 16 m (52 ft) below ground. This functions as an overflow system for the older downtown sewers and flows north (opposite to normal) to the Mid-town Interceptor Sewer. More surprising, were the chambers associated with the automatic diversion process, the largest of which is 5 m (16 ft) diameter and 20 m (65 ft) deep located behind the west shoring wall.

Shoring System

Anchor chose to employ double piles at 3.2 m (10.5 ft) centres along Adelaide and Simcoe Streets, installed in 3 ft (915 mm) diameter holes. Along University Avenue, single piles at 3 m (10 ft) centres were used to allow tiebacks to be skewed where needed to avoid obstructions, such as abandoned Subway shoring piles. Generally, Toronto practice is to take piles to full depth rather than perch them on the rock, following some cases of perched pile failure. Anchor elected to employ pipe "flamingos" for the extensions through the rock. They installed the piles in 880 mm diameter holes using Bauer rigs, but to employ a down-the-hole hammer technique to drill the 12 m (39 ft) deep, 15" (380 mm) diameter, rock sockets (see Figure 3).

Other than at the subway, lateral bracing typically comprised two rows of rock anchors plus a rock pin at the pile rock socket. The combination of one or two upper soil anchors along University Avenue was individually selected and sections drawn for each pile, because of the complex geometry. Tiebacks employed 6" (150 mm) diameter cased holes in soil and 4.5" (115 mm) diameter in rock.

Generally, the 13 m (42 ft) high rock face was assumed to be self-supporting, and no attempt was made to resist the release of the locked-in stresses. Prominent east-west vertical joints appeared as the rock excavation proceeded. These were of concern at the south wall where the jointing was sub-parallel, creating thin vertical slabs with the potential to break loose. Isherwood decided to protect this face with a curtain of wire mesh and rock-bolts. The east and west walls were stable, as also was the north rock face under 200 University. The mesh was used at the remainder of the north face between the existing building and the University Avenue property line.

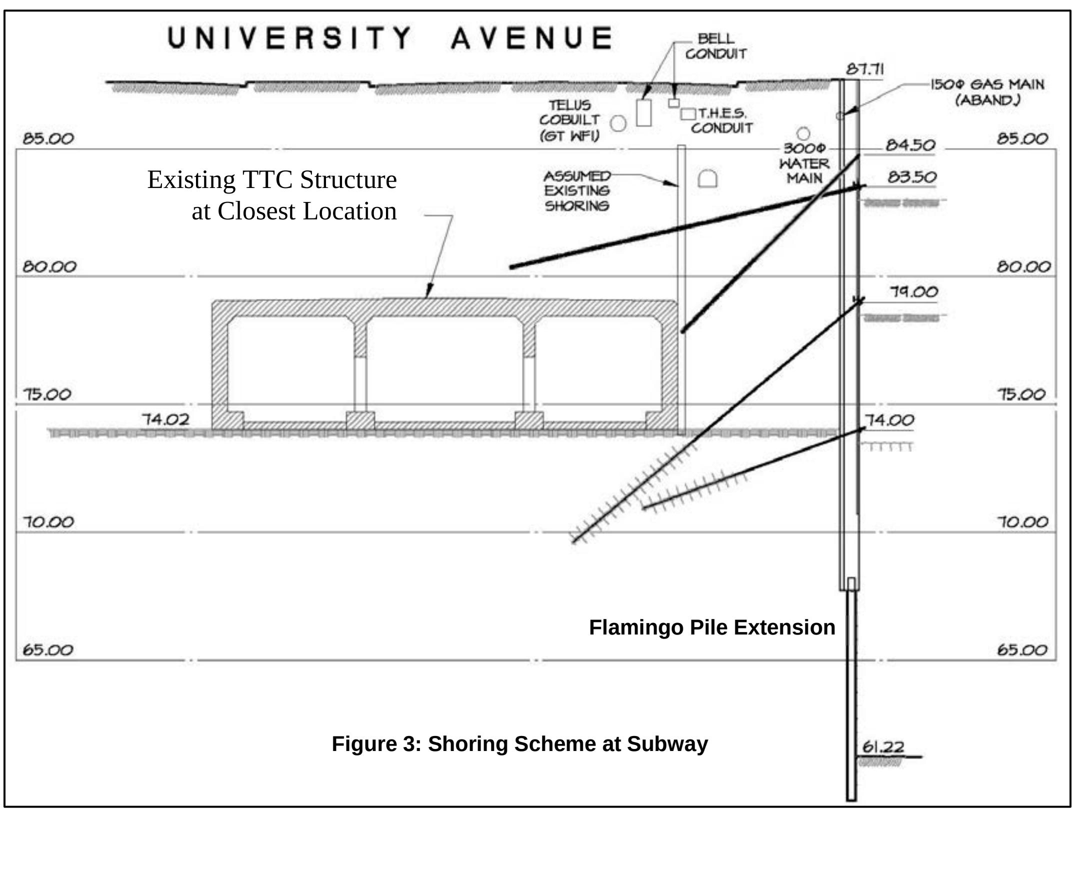


Figure 3: Shoring Scheme at Subway

Under the 200 University Avenue building rock anchors were designed to counteract the weight of the building. Anchors were installed in a grid pattern directly on the rock face. Layout included active anchors at the column lines and passive anchors elsewhere.

FLAC modeling

A two-dimensional Fast Lagrangian Analysis of Continua (FLAC) was used for modeling of the proposed shoring and construction sequence, including pile installation, excavation, shoring and anchor installation, at one location in the centre of the east wall. At each stage, soil and structure behavior was obtained providing soil stress and strain, structural displacements, and axial, shear and moment forces. The model derived soil parameters from the geotechnical investigation conducted by Terraprobe Ltd. and rock parameters from the paper by Trow and Lo (Reference 1). The geometry was based on a 7 m (13ft) clearance between the excavation and the subway tunnel at the centre of the excavated face.

The baseline analysis was conducted with a lateral rock stress of 4 MPa and a rock bulk modulus of 4 MPa. Two parametric studies were also conducted using rock bulk moduli of 3 MPa and 8 MPa. Some of the results are summarized in the table below. The maximum movements predicted are for the 2D displacement at the centre of the excavated face.

In the baseline study, the maximum lateral differential displacement across the total width of the subway box was predicted to be on the order of 10 mm.

Study	Lateral Rock Stress	Rock Bulk Moduli	Lateral Movement Rock Face max top	Lateral Movement of Subway
Baseline	4 MPa	4 MPa	21 mm 17mm	10 mm
Parametric 1	4 MPa	3 MPa	32mm 25mm	17 mm
Parametric 2	4 MPa	8 MPa	12 mm 9mm	6 mm

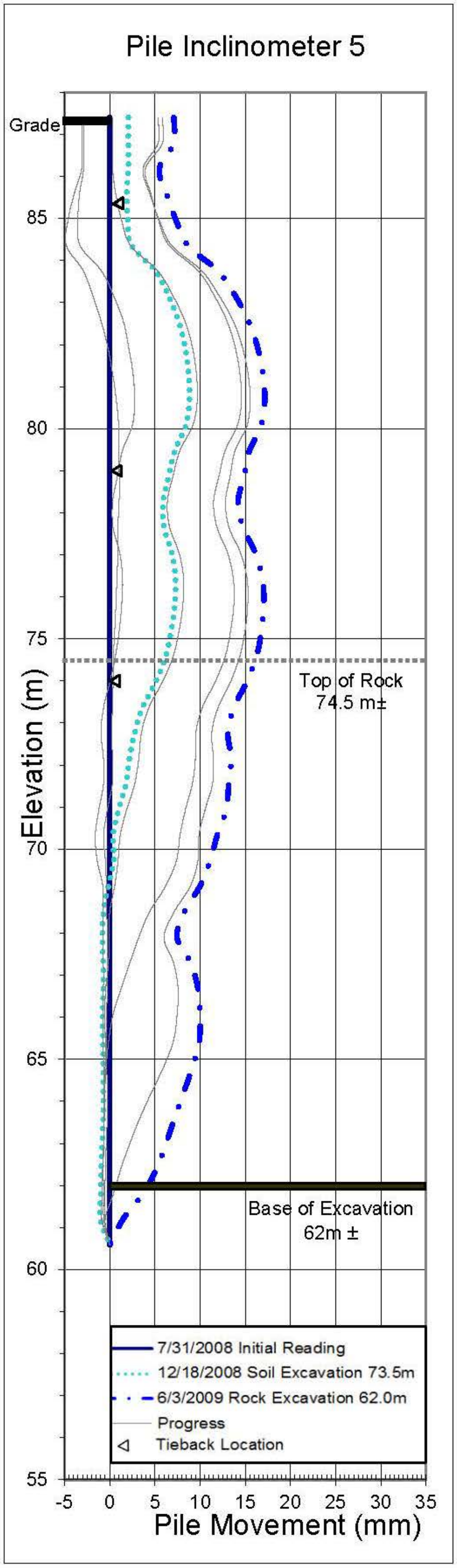
Summary Baseline Analysis

Monitoring Instrumentation

Isherwood standard practice is to attach inclinometer casings to a few soldier piles at representative locations, and targets near the top of each pile for survey monitoring by total station.
At Shangri-La, more comprehensive monitoring was carried out along the east wall at the TTC Subway, and at the north wall for the existing building at 200 University:

East Wall at TTC Subway
A monitoring plan was compiled as part of the TTC approval process, comprising:

a) Pile Targets, affixed to each pile at top and at each tieback elevation as exposed during excavation. Targets were generally read weekly throughout excavation work with an accuracy of 2 mm or better.
b) Inclinometers attached to shoring piles at four equally spaced locations (one was destroyed during construction), plus two placed in boreholes drilled behind the shoring, extending 6 m below the excavation. Inclinometers were generally read weekly during active excavation and had an accuracy of 1 mm or better.
c) Electrolevels installed within the subway tunnels across ten expansion joints to record relative displacement and tilt of the subway box sections in real time. These were read and reported daily with an accuracy of 0.1 mm.
d) Precision Survey Targets established in the subway tunnels at expansion joints to serve as a back-up for electrolevel readings. Accuracy of readings 1 mm or better.
e) Borehole Extensometers installed at three locations to monitor differential rock movement directly below the subway tunnel. These record elongation at sensors 5 m apart along the 30 m length (see Figure 8).



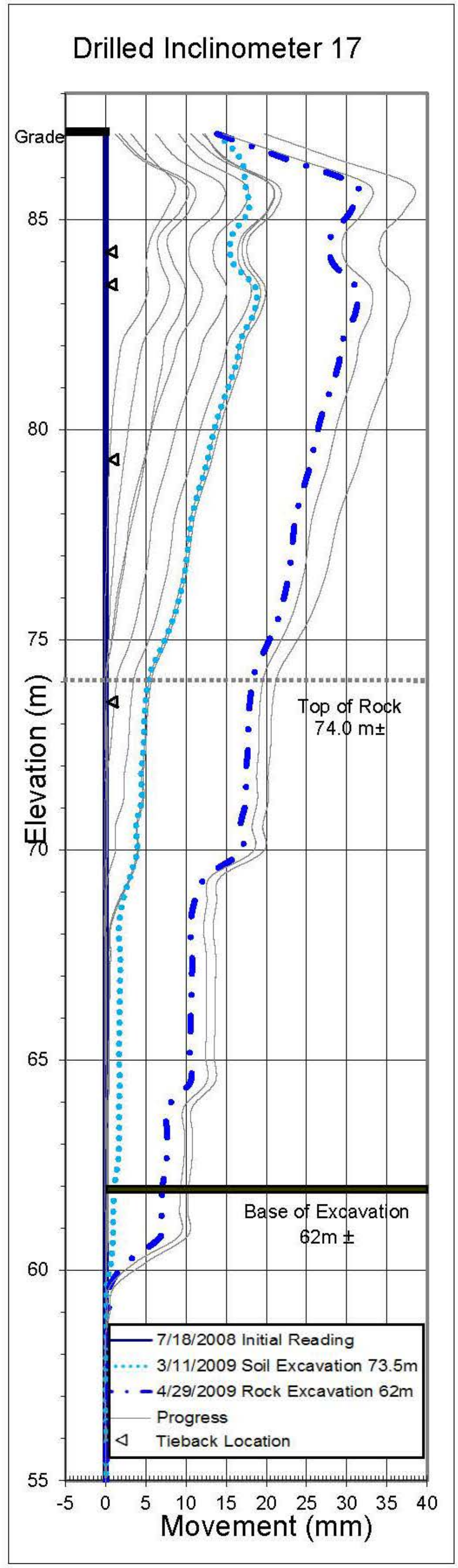


Figure 4: Inclinometer Results

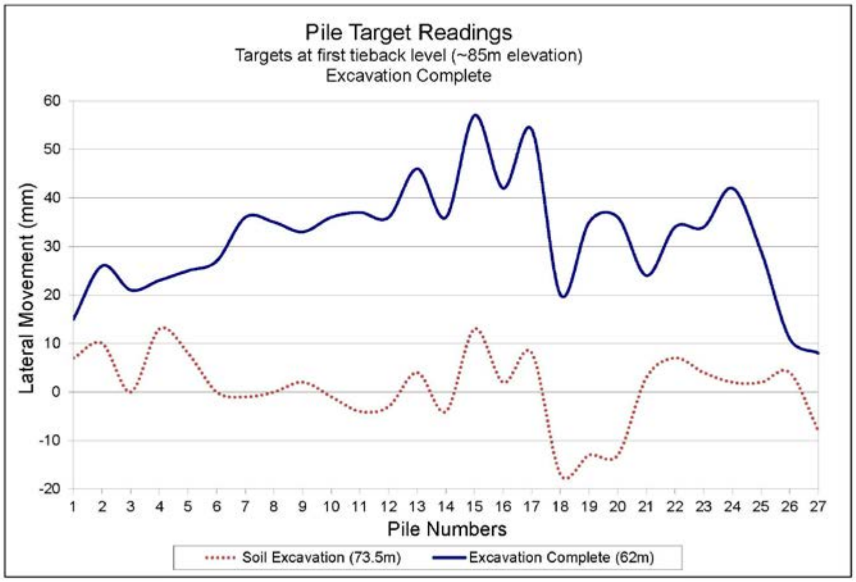


Figure 5: Pile Target Lateral Movement vs. Time

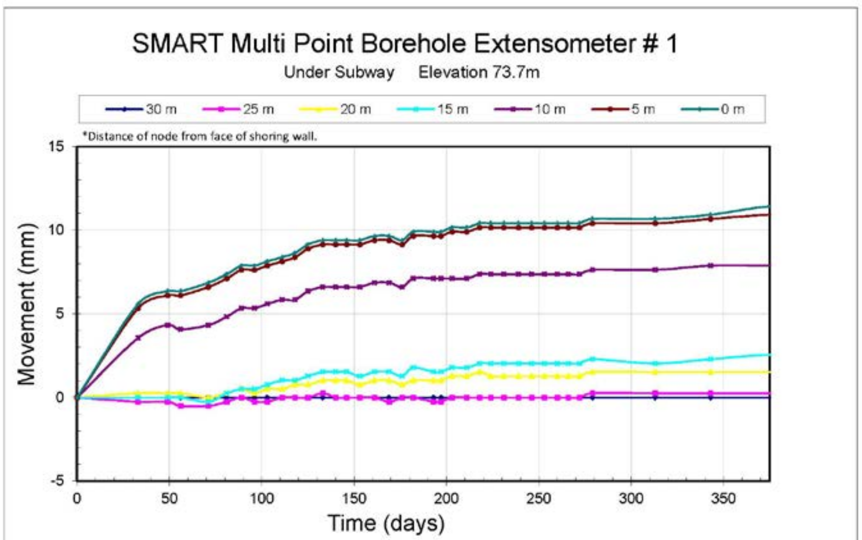


Figure 6: Rock Expansion vs. Time Plot at Subway

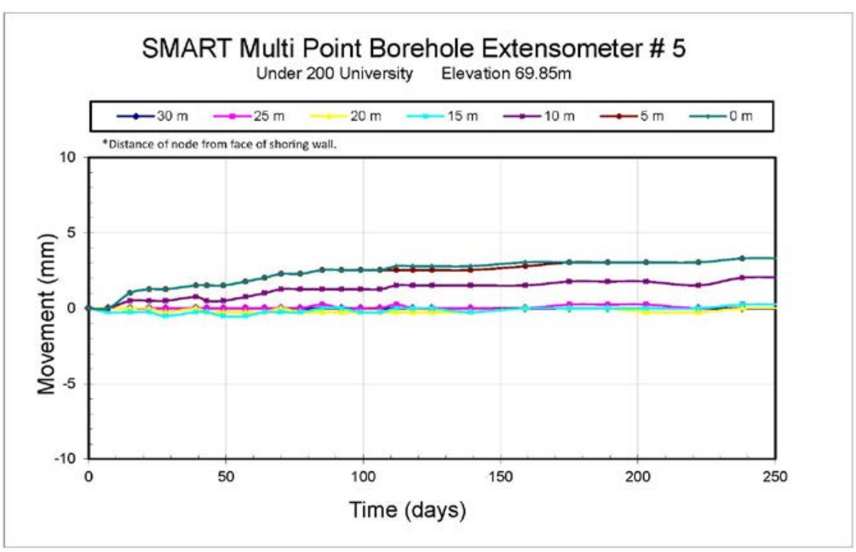


Figure 7: Rock Expansion vs. Time Plot at 200 University

The inclinometer and pile target monitoring indicated that overburden excavation down to the rock surface resulted in shoring wall movements in the expected 15 mm range, and that excavation of the unsupported rock face below resulted in a further 10 to 13 mm, bringing the overburden and shoring with it (see Figures 4 and 5).

The three extensometers gave very similar results indicating lateral movement of the rock just below the Subway of 10 to 12 mm at the face and at the 5 m node, reducing to 7 to 8 mm at the 10 m node, 3 mm at the 15 m node, and 2 mm at the 20 m node, and less than 1 mm at the remaining nodes (see Figure 6).

A comparison with the FLAC predictions (see Figure 8) shows displacement at the near edge of the subway was measured at 7 to 9 mm compared with the FLAC prediction of 12 mm. However the extensometers indicated the rock movement did not extend back to the far side of the subway so that differential displacement across the width of the subway structure appeared to be 7 to 9 mm compared with the FLAC prediction of 5 mm.

The electrolevels indicated that movement across the joints never exceeded 0.4 mm, well below TTC alert levels of 2.0 mm.

North Wall at 200 University Avenue

The existing foundation, located 1 to 1½ basements below the rock surface, comprised a grillage of grade beams along the column grids cast integrally with the lowest floor slab to provide a continuous raft. Because of the potential for rock expansion to cause differential movement the monitoring plan included:

a) Precision survey monitoring of the exterior walls and interior columns.
b) Tape extensometers in north-south arrays within the lower basement.
c) Two borehole extensometers installed in the rock just below the foundations.

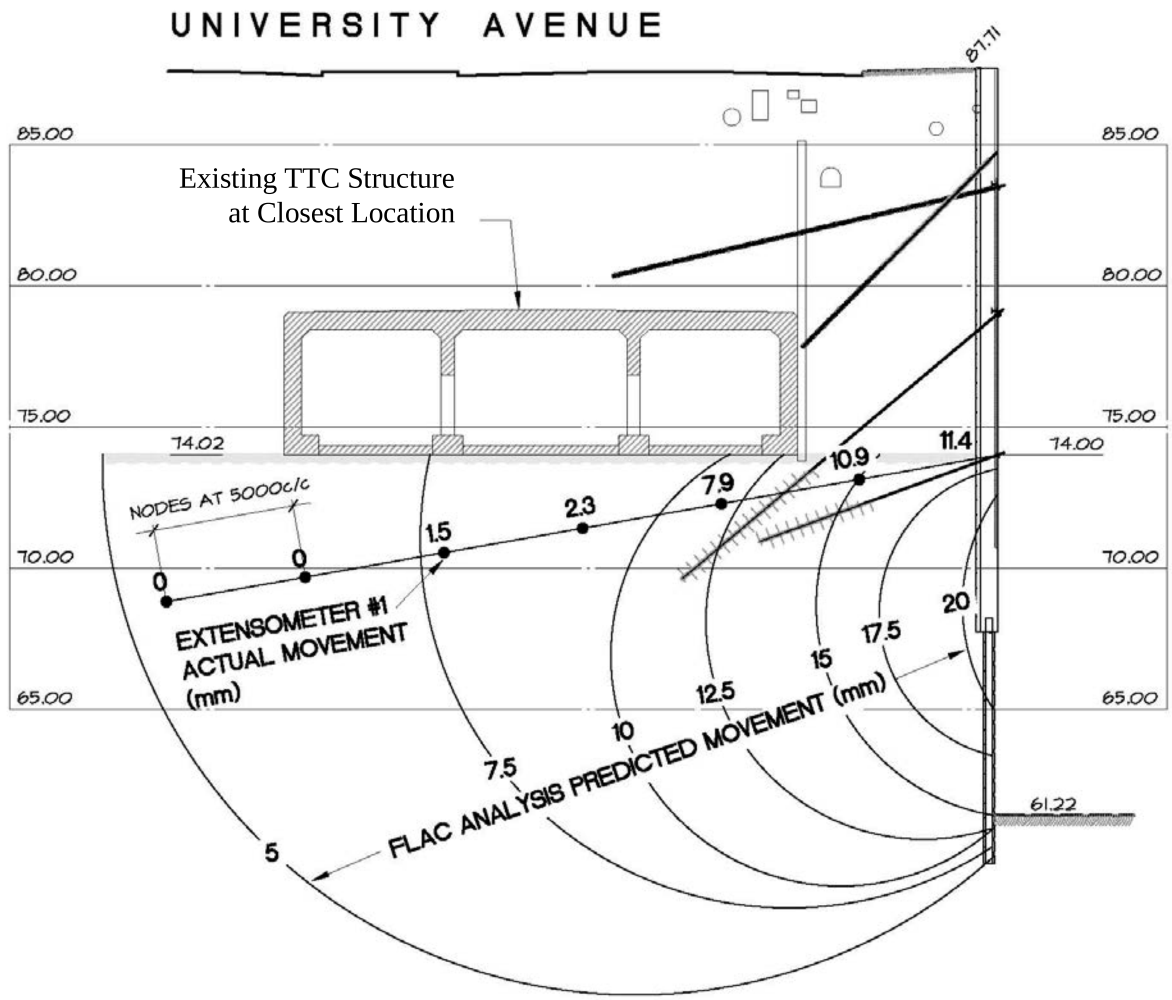


Figure 8: FLAC Predicted Movement vs. Actual at Subway

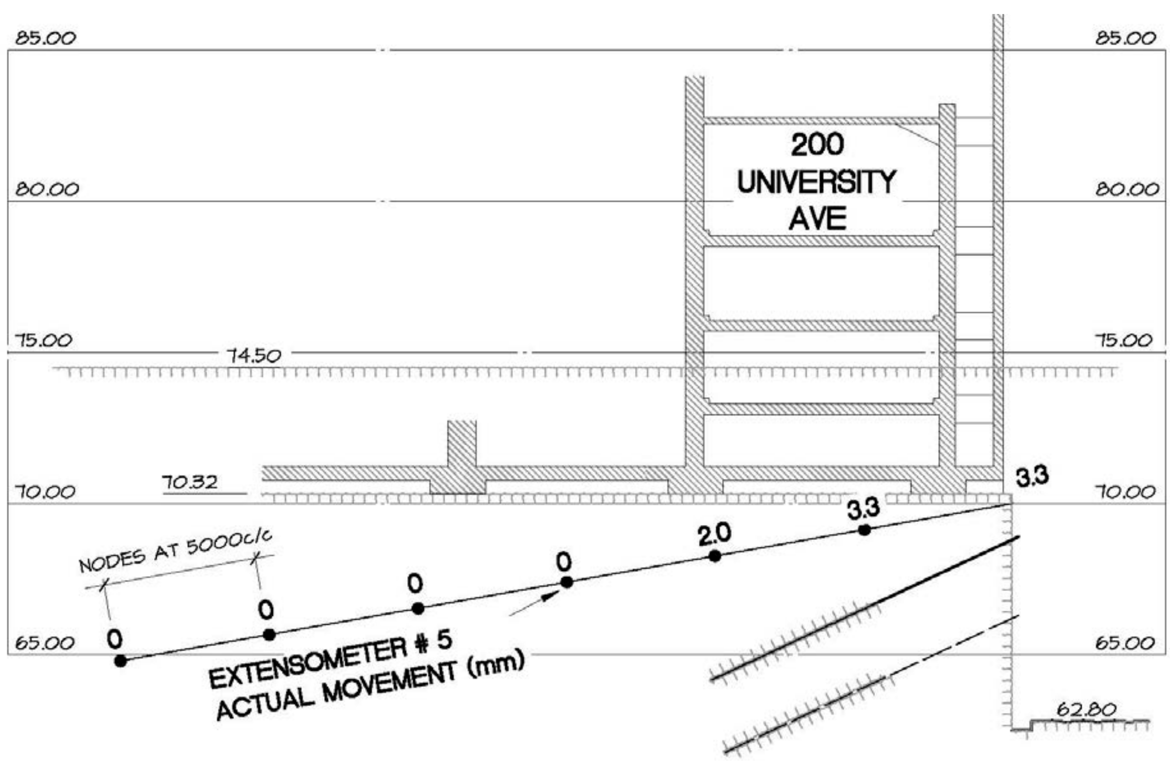


Figure 9. Actual at 200 University

Internal precision survey monitoring of parking level 3 (5th basement lowest level) indicated a maximum of 3 mm into site movement of the building's south wall after new construction was completed to grade. Exterior monitoring on the south wall of the building indicated a maximum of 4 mm into site movement at time of final reading once construction was completed to grade. Monitoring of the east and west walls of the building indicated negligible movement throughout.

The tape extensometer monitoring indicated negligible movement between adjacent columns, with a maximum accumulative movement of 3 mm across the entire building.

The borehole extensometers indicated up to 3 mm of movement at the excavated rock face, 3 mm at the 5 m node, 2 mm at the 10 m node and less than 1 mm at the 15-30 m nodes, consistent with the other measurements (see Figures 7 and 9).

Movements at the north wall were more modest than at the east wall, probably because the 1950's construction of the existing building had removed the upper 5 to 7 m of rock, relieving the locked-in stresses, and the new rock excavation below the foundations was no more than 7 m in height. The largest rate of rock movement occurred under the first two bays of the building during excavation through the first 5 m of rock. Rock movement continued with decreasing rates until excavation was complete.

Conclusions

The design-build excavation shoring scheme realized by Isherwood and Anchor proved to be successful in addressing the serious risks associated with the project. Risk to the TTC Subway was significantly limited by communicating all the potential risks with the owner and reducing the basement footprint, with no impact to the future tower foundations or parking capacity. Constructability of the shoring system, excavation and underground forming was also significantly improved by utilizing the soil on top of and adjacent to the existing subway structure for anchorage of lateral supports.

Isherwood adopted a comprehensive modeling and monitoring program for the North and East shoring walls where risks due to excessive movements were greatest. FLAC modeling of predicted rock movement provided good insight into the extent of total movement and the monitoring program confirmed actual movements were within predictions. The level of monitoring proved to be adequate for assessment of shoring performance throughout construction.

Excavation for, and construction of, the 8-level underground structure was achieved with insignificant impact on the existing structures at 200 University and the TTC Subway, and on adjacent streets and utilities.

Acknowledgements:

1. Professor K.Y. Lo for review of rock behavior.
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4. Paul Kreycir, Anchor Shoring, for comradeship and all those great projects he introduced to Isherwood. Paul died of cancer on February 18, 2011.

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