1. Introduction
This paper presents the designed solution to a unique and critical challenge that was well coordinated and successfully implemented for the use of underground space in an urban environment by the City of Toronto. Several unique aspects of the implementation program are also highlighted.

The new Residue Management Facility of the R. C. Harris Water Treatment Plant in Toronto is a 23 m deep multi-storey underground structure built by cut-and-cover construction method. The existing water treatment plant supplies 44% of the potable water to the City of Toronto and York Region. The newly built high-class underground facility provides environmentally safe solutions for treatment and handling the residue of backwash water produced in the filtration process.

The paper introduces the challenges and constraints of the underground construction from the limited site access, maintaining the full operations of the treatment plant and water supply, to the protection of surrounding sensitive historical buildings. It presents the structures built, equipment utilized, and the techniques and logistics applied for different stages of the construction.

2. Using underground space for upgrading the infrastructure and avoiding environmental and social problems in the city

2.1 History of the project
Constructed in the 1930’s, the RC Harris Water Treatment Plant is the largest of the four water treatment plants supplying the daily water needs for the City of Toronto and York Region. This plant alone supplies approximately 44% of those needs.

Located in the Beaches area of downtown Toronto along the shoreline of Lake Ontario, this 950,000,000 litre/day conventional filtration plant was designed in the classical architectural Art Deco style. The facility was declared a national historic civil engineering site in 1992 and is registered under the Ontario Heritage Act. The plant has been the venue for numerous film and television shoots.

The original design of the plant had the residuals from the water treatment process backwashed directly into Lake Ontario. Subsequent changes in the Ontario Ministry of Environment regulations and the City’s commitment to improve the Lake’s water quality along the local beaches resulted in the City
commissioning a Class Environmental Assessment (EA) for the plant. The outcome of this EA was a recommendation to treat the residuals prior to discharge of the backwash water into the lake.

2.2 Implementing the environmental recommendations
Because of the heritage designation, building an additional treatment facility on site - in the registered heritage park - was out of question. The initial proposed solution was to transfer the residuals approximately 10 kilometres to an existing wastewater treatment plant. After the preliminary design it became clear that this solution would require the construction of certain structures above grade on the heritage site, installation of a 600 mm diameter force main through one of the most valuable residential areas of the city and construction of a new thickening / dewatering / haulage facility. The pre-design team concluded that an improved solution was feasible – using available space to build and completely bury all the structures for the residue management facilities at the RC Harris site, and then reinstate the land above it to its original form.

2.3 Cost-benefit analysis
The new approach was compared to other options using evaluation criteria, such as heritage considerations, capital and life cycle operational costs, technical solutions, protection of natural environment, public health, social, recreation, local business and planned land use. The new approach was superior in all areas but for the temporary inconvenience to the community immediately adjacent to the proposed construction. The positive factors included significantly lower costs, no final impacts to the heritage features of the RC Harris site, and reduced impacts on the natural and urban environment.

3. Design Criteria, Constraints and Solutions
The location of the Residue Management Facility posed several significant design challenges for the design team (CH2M Hill, Canada) and construction challenges for the constructor (Kenaidan Contracting, Canada). These challenges derived from the main conceptual criteria:
- the sizeable new facility be constructed entirely underground,
- the structural integrity and serviceability of the existing heritage buildings and the treated water reservoir under the filter building shall be maintained
- the operation of the filtration plant supplying potable water to the City be undisturbed during construction, and
- after completion of construction activities the heritage site - buildings, topography and features of the green park - had to be reinstated to exactly the original condition, without any impact or visible sign of construction of the underground residue management facility.

3.1 The Designed Structure
The only available land for the Residue Management Facility, with a footprint about the size of a football field, lies on a steep 30-degree slope between the existing Filter Building, the Service Building and the 2100 mm diameter treated water conduits that carry water to the City of Toronto distribution system. The highest roof elevation of the designed structure is approximately 23 m above the deepest point in the facility, the deepest point being approximately 7 m below the water level of Lake Ontario. The structural design is a complex system of multi level tanks and process galleries, reflecting the difficulty of trying to fit the new treatment train into a relatively small footprint on a sloping site. On the plan view, the structure is separated to four main areas (A to D) by various functions and depths.
The two existing 2100 mm diameter treated water conduits further split the area C for three parts, corridors and rooms with different functions.
Two main stairwells are serving the multilevel process areas. Their arrangements and heights of those are comparable to stairs in six storey buildings, but these are completely below grade.

3.2 Soil and rock conditions
According to the geotechnical reports, the underground structure had to be built in various alluvial layers, surface fill, sand and silt, clayey silt glacial till, sandy till with gravelly lenses and silty clay glacial till. The bedrock of the Georgian Bay Formation was located about ten meters deeper than the bottom of the structure. Two distinct groundwater tables were noted in the monitoring wells. The upper one within the sand and silt deposit roughly followed the profile of the slope; the lower aquifer was in the coarse-grained glacial tills approximately at the lake level.

3.3 Foundation and excavation support
The base slab of the main structure supported by 1200 mm diameter drilled reinforced concrete piles (caissons) socketed into the bedrock. To prevent the movements of soils and settlement of the adjacent buildings during the deep excavation for the main structure, the design required caisson wall (secant pile wall) enclosure. Three rows of soil anchors designed to hold the earth pressure on the 10-12 m high secant pile walls. In some areas the reinforced concrete secant pile walls were integrated with the structural concrete walls, by steel studs, creating a permanent composite load-bearing wall.

3.4 Monitoring and Testing
The contract documents included very strict horizontal and vertical movement criteria for the existing structures and the designed enclosure walls. One of the main reasons was that the serviceability of the existing treated water reservoir under the Filtration Building was critical for the City potable water supply. Any movement exceeding the designed criteria could have caused cracks and leaking jeopardizing the water supply of the City, or could have caused a catastrophic failure of the structure, severely damaging the supported heritage filtration building, and flooding the adjacent construction site.
The monitoring system controlled the absolute and relative movements of the targets on the buildings, reservoir and secant walls, automated readings on devices inside the reservoir, vibration control in the plant and the adjacent residential buildings. During dewatering operations the daily volume of discharged ground water was reported as well. The structural piles under the building slab were tested for both compression and tension – to prevent the uplift of structure.

3.5 The Residue Management Process
The design of the residue management process involved the diversion of backwash water through a newly built chamber from the existing plant drain, into the ten new concrete decant tanks where the backwash water is settled and decanted. The decant water is reintroduced through the plant drain outlet to Lake Ontario. Leakage water from the existing plant was also diverted through the new facility and retained for use in the landscaping irrigation system.
Residuals from the decant process clarified and thickened in four reinforced concrete circular thickener tanks, then dewatered to sludge cake with two centrifuges, before being disposed of at an acceptable landfill site. This process required the construction of three chemical rooms, control room and electrical rooms, several miscellaneous tanks and galleries, as well as buried exterior pipes and chambers.
4. Construction Challenges, Risks and Solutions

4.1 Pre-planning of Construction
After in-depth risk assessment, the pre-planning process established the sequencing, construction techniques and logistics for mitigating the potential risks and managing the complex cut and cover construction, which required approximately 100,000 m$^3$ of underground excavation and muck removal, and the construction of the complex structure using 23,000 m$^3$ of reinforced concrete.

4.2 Constraints by Natural and Urban Environment
The constraints imposed by the downtown environment and sensitive residential neighbourhood required strict dust control, noise and vibration control, restricted hours of work and proper traffic management to supply the construction materials at the time as required, and remove the excess earth from the deep level subsurface excavation.

4.3 Challenges imposed by the existing plant and tight site
This challenge was combined with a special topography – steep and sloping towards the lake – a tight construction site, and access which had to be shared with the plant operation. Access had to be maintained through the construction area for regular trucking in of the chemical supplies for water treatment.

The deep working space was limited to the area between the heritage buildings. The access for heavy construction traffic was restricted as this traffic was not allowed to cross over the critical 2100 mm treated water conduits on the west side of the project. Crossing the underground service tunnel on the east side required to build a route on a temporary earth ramp.

The approximately 100,000 m$^3$ of deep excavation - some of them 6m below lake level - required pre-planning and sequencing the excavation. The steep earth ramps for access have been relocated by stages.

4.4 Selection of Piling Technique for Risk Mitigation
The stringent movement criteria set at the design stage for the excavation shoring system along the reservoir and filter building. Any significant movement of these facilities could have resulted in the complete shut down of the RC Harris plant, required special solutions and actions. These were continuous monitoring of movements and vibrations and avoiding any operations inducing vibration. Therefore, the Continuous Flight Auger (CFA) method was applied for installation of secant pile walls at sensitive areas. The CFA operation has several advantages. It does not require casing for the pile drilling and any vibration for moving the steel casings in the soil. The drilled hole is never open; the soil loss is minimal. Either the auger within the soil, or the concrete pumped in when pulling out the auger with soil, supported the earth wall around the pile. Because the CFA interlocking piles stayed above the bedrock level, vibrating operations were not used along the sensitive structures.
4.5 Innovative Logistics for Avoiding Adverse Impacts on the Urban Environment

To avoid the traffic of heavy dump trucks in the busy and sensitive “Beaches” commercial and residential area, the excess excavated earth material was trucked to an on-site temporary dock and removed by barge to a landfill site. This operation was very dependent upon weather and lake conditions, but eliminated a significant negative impact to the urban environment. For the construction of the reinforced concrete structures, two tower cranes were set up. One served area C and the west side of area A and D the other served area B and the east side of area A and B. The cranes lifted the pre-installed reinforcing bar cages in the pre-assembled wall and slab forms. To minimize heavy vehicle traffic in the “Beaches”, a concrete batching plant was set up on the site. This solution minimized the unreliable ready-mix supply through the traffic jammed streets. The aggregate and cement supply was organized to avoid the daytime high traffic periods. This was advantageous for the construction and minimized the negative impacts on the urban environment at the same time.

Figure 6 – Loading the barge for muck removal

4.6 Protection of Undisturbed Water Supply for the City by Value Engineered Building Method

Another example of the importance of the CFA interlocking pile shoring system employed for the support of the existing 2100 mm diameter treated water conduits. These big conduits were encased in concrete, when they were built in the last century. The design proposed to remove the soil around them and underpin in stages. After building the new structure C around the conduits, the design required that a fire exit corridor be built by mining under them. Any significant movement of these old unexplored pipes could have resulted in the shut down of potable water supply from the RC Harris plant. After introduction of a new engineering proposal, in cooperation with the design team, the exit corridor was moved to the top of the structure to fulfill the fire regulations. The pipes were enclosed and isolated within a CFA interlocking pile wall in their undisturbed position. This safer solution did not require the staged underpinning and mining operations under the big old conduits. The vibration free continuous flight auger method minimized the soil loss during installation and met the extremely stringent allowable movement criteria according to continuous monitoring during construction.

4.7 General sequencing of cut and cover construction

The tight area, limited access, and the compact and complex structure determined the pre-planning strategy. The following is a general sequence of work developed during the pre-planning, to optimize the available construction working space.

- Installation of shoring around the perimeter of areas A, B and C and prevent movements of sensitive structures
- Maintenance of stringent criteria, to monitor earth and structure movement adjacent to the existing reservoir
- Installation of secant cut-off wall around area D to retain earth and cut-off water infiltrations 6m below lake level
- Optimize the staging of shoring and excavation to expedite base slab and structural works along reservoir and filter building areas A and B, to reduce risks of unexpected movement
- Protect the 2100 mm treated water conduits and expedite the works on area C structures
- Complete the structural works on area D, close in and make waterproofed all structures and successively provide working areas to the process mechanical and electrical trades according to baseline schedule
- Simultaneously with the process trades complete the interior finishing in the RMF
- Backfill the structures and reinstate the heritage surface features, topography and park
4.8 Special Solution for Backfilling the Roof of the Residue Management Facility

Covering the facility with adequate reinforced concrete structural slab was also challenging assignment for the designer and the contractor. The dead load of the deep and complex reinforced concrete structure and the service load, including various heavy equipment, big diameter pipes and large tanks filled with water was supported partially on bedrock, some alluvial soil layers and concrete piles drilled to the bedrock.

The multilevel sizeable tanks and the open space above them required heavy beams and slabs to create a structurally adequate roof considering all the required safety factors. The demand to carry the full load of earth backfill above the roof structure, which follows the original sloping topography (about 1-5 m earth load and the surcharge of heavy truck traffic on the roads), would have required enormous roof beams and further strengthening of the foundations.

The innovative solution found was to install a lightweight foam backfill above the roof waterproofing and thus minimize earth and topsoil layers above that to keep the structure economical. After some research, the solution employed was to use light and workable Geofoam blocks in lieu of earth.

To build up the Geofoam cover in the shape following the required topography required some innovative “artwork” from the contractor. The foam blocks had to be cut on site and built on the sloping drainage layer to create a solid base for the granular and topsoil backfill. To prevent any undesired movement on the slope the foam blocks were overlapped and interlocked.

5. Conclusions

Thorough risk assessment, pre-planning and careful selection of sequencing, construction techniques and logistics assisted to avoid any significant problems and mitigate the potential risks at the cut-and-cover construction of a new Residue Management Facility. The entire project was built underground and the heritage topography and park was reinstated to its original condition above it.

The major technical considerations included:

- selection of design and construction methods to create a deep and complex underground structure
- unique topographical, geotechnical, hydrological conditions and urban constraints
- site investigations, risk analysis and detailed risk assessment in the pre-construction stage
- extensive monitoring during construction to assure the safety of existing structures and,
- protecting the well-being of inhabitants in the urban area affected by the construction of the new facility in underground space.

It is worth mentioning the several successful and/or innovative technical and organizational solutions for consideration at future cut-and-cover underground constructions:

- Thorough risk assessment and pre-planning of construction operations
- CFA interlocking pile wall with soil anchor supports for deep excavations along sensitive buildings
- Complex monitoring and automated signalling/alarming system
- Sequenced excavation work with staged ramp relocations
• Removal of excess excavated material by barging operation
• Using prefabricated rebar panels and pre-assembled wall and slab forming panels
• On site concrete batching plant to assure continuity of big pours
• Complete isolation of existing sensitive structures or pipes by CFA interlocking pile walls
• Sequenced and simultaneous operations to optimize the trade performances in tight working space
• Foam block backfilling on the roof of cut-and-covered space to reduce the load on the structure and foundation

The interesting and innovative use of underground space in a unique location made it possible to complete an environmental upgrade to the RC Harris water filtration plant in Toronto. The environmental and social objective has been to maintain and improve the ground surface amenities provided to the public, in a densely built-up downtown area, along with protection of the heritage land and buildings.

*Additional images of the construction phases*