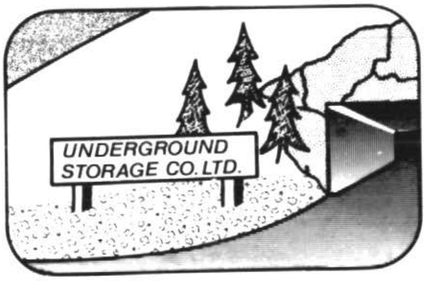

Underground Construction in Canada: Some Aspects of a Promising Avenue in Geotechnical Engineering

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Introduction

The use of underground space in Canada has long been restricted to tunnels for trains and cars and to hydroelectric power rooms (Churchill Falls, James Bay power stations). Some pioneer earth-sheltered housing and domestic storage has also been reported in Quebec, Ontario and in the prairies.

Today, Canadians are more and more aware of the great potential of the underground and more diversified projects are already completed or underway for the near future. This article tries to portray the Canadian experience in the underground, aiming at a better comprehension of the processes that underly their successful completion.

Past and present uses of underground space in Canada

The use of underground space in Canada dates back to the start of the colony, and especially in the years 1679–1780, when pioneers were building storage units under their houses. Those vaults were dome-shaped and were built after the whole house was completed; approximately thirty of them can still be seen today in Quebec City. Some of these vaults have been restored and used as cellars, taverns and storage space (Figure 1).

Protection against climate extremes. Protection against climate extremes in Canada by the use of the underground is not well documented, although there is local evidence of the use of the thermal retention of earth-sheltered units in the prairies and in Quebec and Ontario where earth cellars or "cold rooms" were built and covered with earth or peat.

Actually, Canadians are rediscovering the advantages of earth sheltering especially since energy costs have started to be of national and individual concern. Up to now though, very few earth-sheltered houses or buildings have been constructed in Canada; surely this is related to a limited awareness of the energy savings that can be attained. But we believe that our traditional surface-thinking habit is a more serious obstacle to overcome. Possibilities certainly exist since important and valuable work in this field has been done in Vermont and Maine where the climate is very similar to southern Quebec and Ontario. There are also great similarities between the climates of Canada and Scandinavia, the latter a country where underground construction is well developed. We would also emphasize the fact that Canadian architects and urban planners are neglecting the use of solar heating within earth-shelter design.

Conversion of old mining works. Canada is well known for its underground resources such as iron, metals, asbestos fibres, etc. and mining activities date back to the 1800's. In Quebec for instance, extraction of copper, chromite and asbestos fibres has left over 1,000 underground and open-pit excavations without any rehabilitation. In the southern part of this province, of a total of 450 mining sites registered, only one underground chromite mine is known to have been converted to a secondary use; it is now a water reservoir for use in case of fire (Boivin, 1981).

The great distances between the mines and urban settlements is one important reason why rehabilitation does not take place; another reason is inefficient or unagressive laws and regulations. The remoteness of the old mining works explains why this type of underground space is not of very great appeal; these abandoned excavations are often left filled with water and continue to remain a public hazard and an environmental problem.

Potential secondary use of excavated space is much greater in the Niagara Escarpment (Roegiers, 1981) in Ontario, but serious legal problems prohibits Ontario from developing a second "Kansas City". In fact, very complex legal constraints related to ownership of surface land and mineral rights exist in some provinces in Canada that will hinder efficient rehabilitation of mines and quarries and the use of underground space in general.

Underground use in the urban areas. In a country as vast as Canada, lack of space would seem at first surprising. But since Canada is a northern country and since most of its population lives in the southern areas around the Great Lakes and the St-Lawrence River, lack of space appears as an increasing problem in cities surrounded by valuable mountainous or agricultural terrain. Some provinces like Quebec and British Columbia have laws now that protect agricultural land from urbanization; this situation forces the municipalities to densify their land use and to use airspace as well as underground space for certain urban functions (public transport, highways, parking areas, commercial malls). This is especially evident in cities like Montreal, Toronto, Ottawa and Vancouver where underground space is used to solve urban density problems such as safe pedestrian circulation, high winter commercial activities, car parking and urban transport systems.

Canadian underground construction does exist and will be described in three main categories: public utilities, communications and other urban uses.

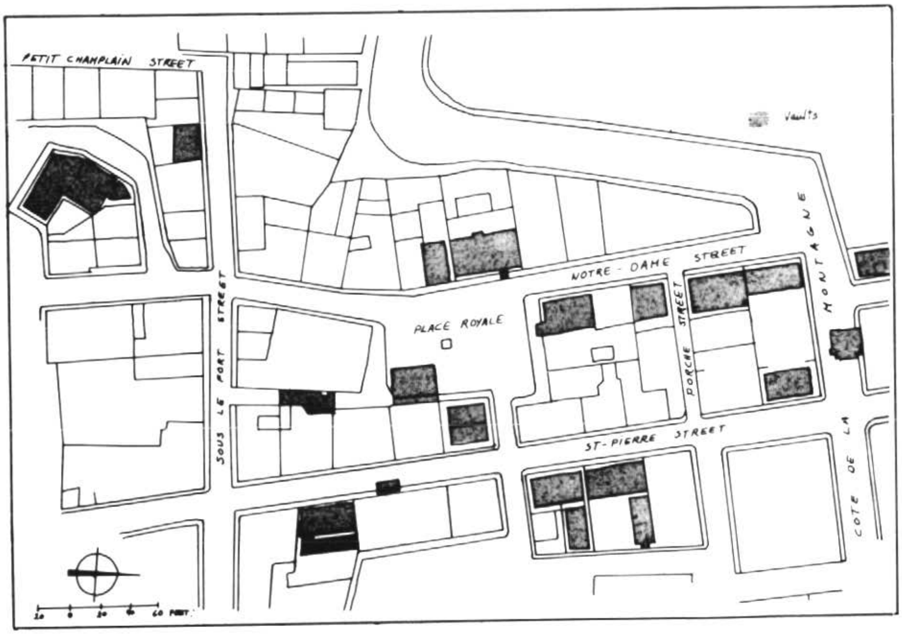


Figure 1 *Dome shaped vaults in Quebec City at "Place Royale".*

Utilities. Exception being made for housing in northern Canada, where the utilities have to be grouped above ground in special ducts called "utilidors" to prevent ground disturbance by thawing, all the utilities in Canada are located under the street network at a depth equal or greater (2-3 m) than the winter frost penetration. In less densely populated areas the buried utilities are mainly gas, aqueduct and sewers put in place by the cut and fill method. Repairs require costly and disruptive reopening of trenches in the streets and sidewalks. Because of local geological conditions the economic advantages of this solution generally outweigh the drawbacks; granular Pleistocene deposits occur nearly everywhere with a minimum thickness providing stable ground and little water inflow.

In the cores of our cities, telephone cables, electric cables and district heating are also placed underground by cut and fill and are serviced from the surface. Deep tunnels commonly 20 m below surface, but down to 50 m at some places, have been driven in the last ten years by conventional and TBM (Tunnel Boring Machine) methods for the replacement of main aqueduct and sewage treatment plants. In Montreal Island, the sewage water interceptor tunnel (Fig. 2) will circle all around the perimeter of the Montreal Urban Community for a total length of 120 km to connect with all of the existing direct-to-river sewers. Dubnie and Geller (1975) have described the existing works of this type in the ten provinces of Canada.

The preferred construction method for the larger utilities is tunnelling in the rock substratum at a depth sufficient to provide the best geotechnical conditions for tunnel driving and to avoid any of the surface occupancy constraints. In rare occurrences the local geology and project design require tunnelling in soft deposits such as marine clays (Eden and Bozozuk, 1969). Wide structures such as aqueduct water reservoirs, parking lots at Kingston, and water purification plant at Mississauga (Legget, 1975; Harvier, 1980), covering several tens of thousand square metres, were buried at a shallow underground level by the cut and fill method. Their finished ground level surface is converted into urban recreational parks.

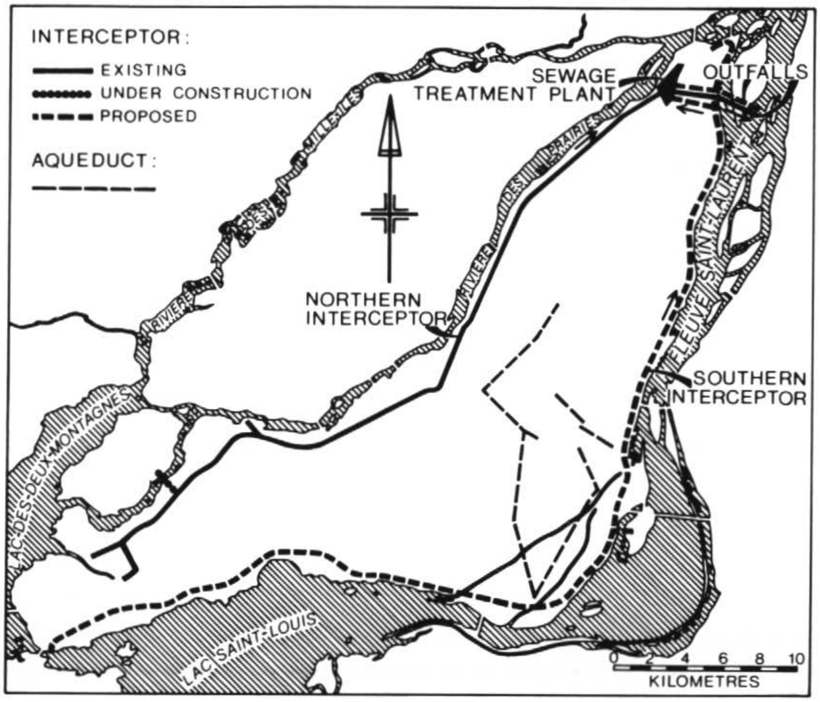
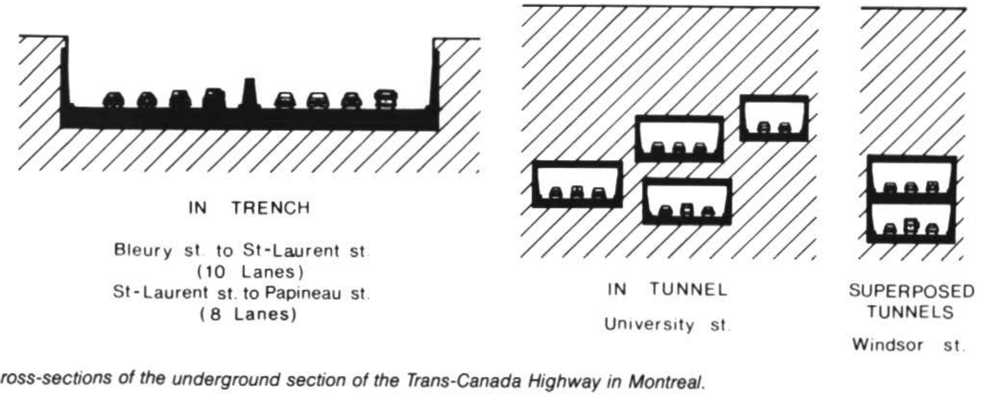


Figure 2 *Map of the main new interceptor and aqueducts in the Island of Montreal.*

Communications or transportation. The second most important users of urban underground space are transportation systems. In Canadian towns the railway network is less important than in European cities for passenger traffic; the network is a century old and only recently has it been modernized for utilization as a mass transport system. The old railways built in the past on the ground surface now create unpleasant barriers enclosed by the expanded urban areas. More recent systems like urban expressways are constructed on elevated or depressed sections. The 5 km long Mount Royal railway tunnel constructed between 1912 and 1916 through the Mount Royal Hill in the middle of the city of Montreal stands out as a remarkable exception. Its terminal, the Central Station, was constructed at the same time 12 m below the street level in an excavation that required nearly as much earth and rock removal (323,000 m^3) as the volume of the main tunnel (Bushfield, 1919).

Both open trenches and closed tunnels have been designed in underground urban expressways so they would not interfere with surface streets. Figure 3 shows a typical cross-section of the Trans-Canada highway in downtown Montreal. The open trench design is an economic compromise between a truly underground expressway and a surface highway but negative environmental impact such as high noise levels remains to such an extent that it raised opposition among citizens. This kind of opposition has been sufficient to stop projects in Toronto and Montreal in the past. The costlier tunnel sections of the same highway eliminates these negative impacts. A 1 km long tunnel of the downtown expressway of Montreal is worthy of mention because it comprises an underground interchange excavated by tunnelling in rock to a depth that reaches 30 m below the surface. Its construction was complicated by the existence in that area of the greatest density of surface and underground structures, in-


IN TRENCH

Bleury st. to St-Laurent st.
(10 Lanes)
St-Laurent st. to Papineau st.
(8 Lanes)

IN TUNNEL

University st.

SUPERPOSED TUNNELS

Windsor st.

Figure 3 *Typical cross-sections of the underground section of the Trans-Canada Highway in Montreal.*

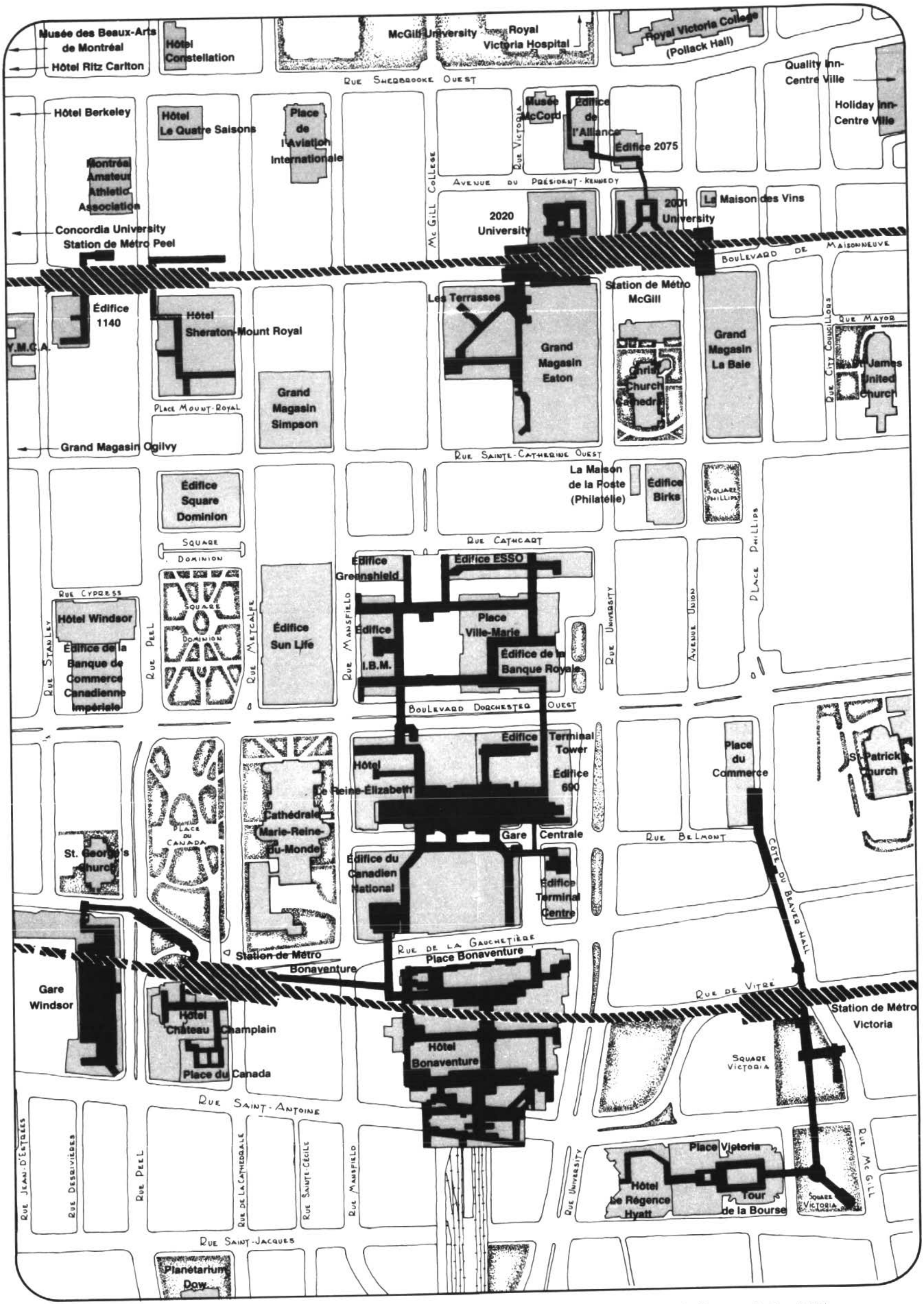


Figure 4 *Part of the Metro and pedestrian underground network known as the "underground city" in Montreal. (Source: Boivin, 1982).*

cluding a Metro station that suffered minor displacement due to stress relaxation; both structures being sited in thinly stratified Ordovician limestones.

Rapid Transit Systems or Metros are now the most important users of underground space in two major Canadian cities: Toronto initiated its system in 1954; it is 80% underground; Montreal opened its completely underground Metro in 1966 just in time for Expo'67. Both networks now comprise more than 50 km of tunnels and are being expanded by new lines. Vancouver and Edmonton (Eisenstein and Thomson, 1977) have also started construction of rapid transit systems partly underground.

Metro structures stimulate the adjacent underground space utilization as most stations are linked underground to commercial and office buildings. In Montreal, the heart of 13 km of pedestrian corridors (Figure 4), one to three levels below the streets, started with a project of modernization of the Central Station that still had in 1960 its original location at the bottom of a trench left open since 1916. The construction of the Place Ville-Marie project more than 20 years ago now serves as a model for many cities around the world which adopted soon after a similar concept of what is still called "the underground city". In cold climate countries the popularity of an integrated network of underground train and Metro stations, shopping malls, transit corridors between buildings, etc. was immediately evident; in Montreal during a cold day of winter the downtown area might seem quiet at the street level because all the activity is concentrated below. Some new large buildings in the central district add to this system and provide links to the existing underground complex (Bell-National Bank Towers, Guy Favreau Complex, Palais des Congrès).

Other urban uses. Aside from uses of the underground that imply circulation (water, pedestrians, vehicles), some space is reserved for different human occupations (Boivin, 1982). In Quebec City for example, the music conservatory is located underground next to "Le grand théâtre" (Labs, 1976). This building consists of two underground levels with approximately 40 small cells per storey where students can practice their musical instruments without disturbing one another. There is a central open courtyard that distributes sunlight and serves as a small outdoor oasis in the summer where concerts are given (Figure 5).

In Edmonton, the Sherwood Park Catholic School has been built as an earth-sheltered structure (Campbell, 1982). Heating bills for this type of underground courtyard building are expected to be around 60% of those of a conventional surface school, which represents savings today of $4,000 per year.

Another earth-sheltered school exists in Brandon, Manitoba, which emphasizes relations with the exterior through a central skylight and windows in corridors.

Underground protection. Canadians are not well informed of the existence and location of shelters in case of war. In fact, our attempts to quantify the number of possible shelters in Canada have led to disappointing results. Very few well-equipped and functional bomb or fallout shelters do exist in Canada and only a small percentage of the population would find refuge. Studies conducted for Emergency Canada to identify and search for possible shelters included basements, underground parking garages, tunnels and other underground installations that could only be used for very short-term protection since they are not equipped with basic utilities such as toilets and drinking water.

The Royal Canadian Air Force also has operated a "hardened site" for twenty years now. The NORAD underground facility near North Bay (Ontario) is an integrated, autosufficient complex driven into a granitic mountain (Margison, 1977). The installation has two access tunnels (north and south), three main groups of chambers with a diesel power plant and a storage chamber for cooling water, two vertical communication and gas drill holes as well as a diesel exhaust shaft.

Industrial and high level radioactive wastes. Industrial solid and liquid chemical wastes have been buried in quarry pits and disused mines since the beginning of their production. This practice existed before recent environmental regulations enforced more appropriate means of disposal.

Today some industrial wastes are being placed underground, mainly by primary industry, in the hydrocarbon and mine fields. Liquid wastes, mainly oil field brines, waste brines from solution mining of salt, refining effluents and liquid chemicals are injected to depths of 500 to 2000 m in the western provinces and also in Ontario (Simpson, 1976). Mine storage of solid wastes is restricted to wastes from excavation and milling operations of the mine itself. Distant location is the main factor prohibiting the conversion of the numerous existing mined-out cavities in Canada.

In urban areas, in nearly all cases of backfilled quarries now enclosed by urban expansion, the fill includes various proportions of wastes from demolition and domestic sources. Backfilled quarries now constitute a hazard for adjacent underground development mainly because of the possibility for methane gas and other pollutants to migrate through rock fractures.

The question of high-level radioactive waste produced by the operation of CANDU nuclear power plants has received a lot more scientific and engineering attention. No underground facilities are in operation in Canada as the spent fuel is kept in deep pools at each power plant, but Atomic Energy of Canada has devoted many studies to elaborate a conceptual design of their own for the permanent disposal of this dangerous byproduct (Charlwood and Gnirk, 1977; Mayman *et al*., 1976; Brown and McEwen, 1983). The proposed repository will be large enough to accommodate all the estimated 700,000 tonnes of spent fuel from Canadian nuclear power plants that are expected to be in operation by the year 2025.

Granite or gabbro plutons are being studied as the host rock for an array of vaults location 1000 m underground. Chambers will spread over 3 to 5 km^2 depending on the spacing that will be retained for the final design. The hard rock of the stable Canadian Precambrian shield offers the required very

Figure 5 *Quebec City's underground Music Conservatory with its central atrium, two stories deep.*

long-term security for a permanent repository. Fracture studies at many sites demonstrate that even the event of a glacial ice sheet invasion in the next 250,000 years would not affect the rock below 500 m. The other possible solution of storage in salt beds or shale have been put aside because these rocks occur in more tectonically active parts of the country.

Final site selection and design requires additional studies, mainly on thermal rock mechanics, hydrogeochemistry and in the evaluation of natural stresses in Precambrian plutons of the Canadian Shield in Ontario where the future site will probably be located.

Hydroelectric power plants. Canadian electricity is mainly produced from its abundant hydro resources. It is not surprising, therefore, that many of the largest underground power houses are in rock. Churchill Falls in 1971 and, more recently, LG-2 power houses, each having an installed capacity of over 5200 MW, have owned the world record for size. The machine hall at LG-2 on La Grande River, James Bay area in Quebec, is 483 m long with a section of 26 × 47 m. The total volume of excavation required for the various chambers of the power house reached 2.8 million m^3.

Future Uses of Underground Space

We will discuss here the advantages and limitations of some of the interesting perspectives considering the specific Canadian conditions.

Hydrocarbon Storage. Large storage of hydrocarbons in excavated caverns or existing mines has been studied at various levels of advancement; the first project to be started is the Wesleyville storage facility that will supply an Ontario power station with 4.8 million barrels of oil. The caverns have a cross-section of 10 × 16 m excavated 70 m below ground level in a stratified argillaceous limestone. Much larger projects are being studied on the Atlantic coast in Newfoundland and Nova Scotia to serve as strategic supply for Eastern Canada and U.S.A. The disused Wabana iron mine under the seafloor near Bell Island, Newfoundland, could allow use of existing man-made cavities in Ordovician sedimentary rocks, of more than 15 million m^3, as a very low-cost storage facility for crude oil. A competitive project in the Canso Strait area (Nova Scotia) consists of two salt mines that could be adapted for storage.

Natural gas is overabundant in the Prairies and in the Arctic, but its use throughout the country has been long-delayed by transportation and storage deficiencies. In Alberta, Saskatchewan and Ontario (Simpson, 1977) underground gas storage is commonly achieved in depleted hydrocarbon reservoirs and other permeable rock strata near producing fields and existing pipelines. Gas consumption everywhere in Canada is now an important element of governmental energy self-sufficiency policy; new needs for storage will come with the expansion of the distribution system in the eastern part of the country. Aquifer storage is considered as a low-cost solution achievable in every province of Canada.

Underground Power Stations. The general success, in the past twenty years, of the underground concept for standard hydroelectric power plants in Precambrian rock has encouraged research in the application of the same solution to other types of power plants, such as nuclear power stations. Lindbo and Oberth (1980) have presented a critical review of the development of the concept.

Ontario Hydro has conducted preliminary research (Oberth and Lee, 1980) for the underground siting of CANDU nuclear station in southern Ontario; the study was site specific and the preliminary design was for a 4 × 850 Mw power plant in Precambrian gneiss at a depth of 400 m (unlined caverns). The rock chosen appeared the most suitable for such an important structure although the natural high horizontal stresses and the thermal behavior of the rock during a loss-of-coolant accident would be critical. The problem of high horizontal stress can be overcome by a proper orientation of the caves along the direction of the largest horizontal stress. The thermo-mechanical effect of an unlikely serious accident would consist of a change in the stress distribution around the excavations, which could induce compressive failure and spalling at the crown and the floor. Haimson and Lee (1980) discussed these effects and their solution.

Underground nuclear power plants present interesting advantages of increased confinement, protection against acts of war, sabotage and natural hazards like earthquakes, but the construction costs are estimated roughly at one-third higher than the standard surface siting.

Underground pumped hydro power stations have also been studied in Eastern Canada, because of the very limited opportunities offered by the low topography for the installation of surface pumped hydroelectric power plants. Pre-feasibility studies in Quebec have indicated the local advantages of creating the lower reservoir in an underground excavation at a depth of 600 m, where excellent geotechnical conditions could be encountered for the economic excavation of large openings totalling 3.5 million m^3. The upper reservoir location presents few problems because of the occurrence of numerous large rivers and lakes near populated centers.

The Oil Mine Concept. Tunnel driving for the recovery of hydrocarbons in granular deposits was used in the nineteenth century at Pechelbronn in France. One century later the same method might provide a solution to the problem of the recovery of bitumen from the deeper layers of the Athabaska Oil Sands. Chatterji *et al.* (1979) have noted, in the only existing tunnel in the tar sands at Saline Creek, near Fort McMurray, that the driving of a tunnel releases gas pressure and the resulting swelling reduces greatly the "in situ" strength. Mining the deeper strata would produce far less disturbance of the surface than the extraction of bitumen from the shallow (0-60 m) layers by strip mining. However, geotechnical problems make the oil mine concept a difficult, but not impossible, task. Tunnelling from shore to an undersea oil field is considered feasible by many workers. McCusker and Tarkoy (1976) discussed the application of the oil mine technique for Arctic oil and gas fields. It presents definite advantages both for extraction and transport; pipelines will have to cross water from island to island and the tunnelling solution could bypass the very difficult conditions of the Arctic sea. The Paleozoic sedimentary rocks of the Arctic basin are not significantly different from sedimentary rocks through which several thousands of kilometres of tunnels have been driven; but the effects of permafrost under land areas requires additional studies.

Conclusion

Canadian underground installations are more numerous than we usually think and their number is increasing year after year. These installations are however far apart from each other and this is due mainly to the great vastness of Canada; underground structures thus are perceived as isolated and special exceptions to the general rule of surface construction.

Nevertheless, underground development in Canada has a great potential mainly because of favourable geological environments; the Canadian Shield shares the same geotechnical characteristics as most Scandinavian rocks where underground development is now intensive. Other areas of younger rocks offer generally very good conditions.

The Canadian experience in the underground is not to be ignored; we made our name in the hydroelectric field and in the pedestrian commercial network (Ponte, 1971), which are the most renowned structures. We are now moving forward into other possibilities such as sewage treatment plants, repositories for radioactive wastes, and other urban construction.

Essentially, the increase of underground space use is related to the general knowledge of the vast possibilities offered. Our earth science specialists are certainly capable of dealing with this new domain of interest.

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