Unconventional Uses of Underground Space

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1. Introduction

Human have used underground space ever since their existence. Some of the oldest discoveries of caves inhabited by modern Homo sapiens include the Jebel Qafzeh cave near Nazareth in Israel, dated to 92,000 years ago, and the Klasies River Mouth caves near Cape Province in South Africa, where it is believed that anatomically modern humans lived over 125,000 years ago. The early use of underground space was mainly for shelter and protection from the elements and wild animals. However, with the development of tools and advancement of civilization man built underground shelters and used underground spaces for dwelling, protection, defence, storage, etc. Some of the earliest tunnels were built over 4000 years ago around 2100 BC in Babylonia. These tunnels were used mainly for irrigation but some tunnels were also used for pedestrian passage under the Euphrates River connecting the royal palace to the temple. However, the intentional use of the underground space in recent history remained limited until the late 19th and the early 20th Century when the needs for tunnels and underground spaces became more urgent and the development of tools and techniques that would allow their excavation became available. Nowadays, the use of underground is associated mainly with transportation (e.g. roads, rail, and transit) and conveyance of liquids (e.g. water and sewer). This paper discusses unconventional uses of underground space and the benefits of such uses. It provides a historical perspective, potential future uses, and addresses the economical and environmental benefits of the use of the underground space.

2. Needs and Benefits of the Use of Underground Space

In the last few decades, underground space became increasingly important for the development of societies. Population growth, growth of metropolises, scarcity of urban land, environmental awareness, and specific needs for protection, storage, security, and sheltering encouraged the use and the development of underground spaces.

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Figure 1 Megacities – Source – “Megacities and our Global Urban Future” 2005 – Earth Sciences for Society Foundation, The Netherland
Population growth and the movement of the people from rural to urban areas resulted in significant demands for growth in cities infrastructures especially in megacities throughout the world. Such growth can only be supported by the use of the underground space. It is estimated that by 2015 over 60 megacities, each with a population of over 10 million people, and collectively housing more than 600 million people will exist in the world. And it is expected that this trend will continue throughout the 21st Century. See Figure 1. In 1800, only 3% of the world population lived in cities, a figure that has risen to 47% by the end of the twentieth century. It is expected that by 2030, 60% of the world population will be migrated to cities and the largest cities will grow even larger creating more megacities with limited spaces, facilities, and supporting infrastructures. This shift in population centers necessitates the developments of infrastructures in cities to support the population surge including provisions of efficient transportation systems; reliable utilities such as power, water sewer, and communication systems; and supporting infrastructures. The logical location of these systems is underground. Furthermore, the scarcity of available land in megacities and the wide spread of the adjoining suburbs invite the use of the underground space for untraditional purposes such as commercial, institutional, and service facilities.

Environmental deterioration in and around megacities, and the increase of people awareness of the need of sustainable development invite the use of underground space. Increasing the demand for better living conditions in urban areas can be achieved by placing infrastructure facilities, utility distribution, transportation systems, and other supporting structures in underground space. In the last few decades, many major cities in the world started placing many of its facilities and urban services underground and developing real underground cities.

Extreme weather conditions in certain places suggest the use of underground spaces for various facilities including commercial uses such as shopping centers, institutional uses such as libraries and museums, and recreational uses such as sport venues, theatres and concert halls. The use of underground space in these conditions often provides better environment control, better insulation and less power consumptions.

Underground spaces sometimes are available from previous use such as abandoned mines or war-time shelters that can be easily converted into underground storage facilities, experimental facilities, or recreational facilities. They can be developed cheaper and provide the needed services and protection. Often in center of cities, the use of underground space is inevitable because of the congestion of city centers. Such space can be developed with significantly less disruption to adjacent facilities and the public. It will have less visual impact, better air quality and less noise. The development of underground space in city center for commercial, institutional, or office facilities will enable the space above ground to be developed into open green spaces for recreational uses making city center more inviting and healthy. Furthermore, placement of transportation systems including highways, transit, and rail systems in the city center underground will reduce congestion and associated air and noise pollution.

The use of the underground space provides significant direct and indirect benefits. In general the placement of the lesser facilities underground such as parking, utilities, storage, transportation etc... provides the opportunity to develop the land for better and nobler purposes such as residential, commercial, or recreational facilities and green spaces. The multiuse of the land enhances the quality of life and provides environmental and economical benefits to the users and to the society at large.

Underground space provides opportunities for better urban development. The use of subsurface space for commercial, institutional, or other functions provides additional opportunities for better utilization of the land above ground. For example building an underground sport arena or a shopping center while developing the area above it for outdoor recreational facilities or providing green spaces allow multiple uses of the land. Often these developments are extended several levels below the surface with various functions at various levels such connections to a transit system, underground parking, commercial levels, services, and connections to office buildings, or other above ground developments. This creates the opportunity for increasingly dense development and a more efficient use of the urban land. It also provides the opportunity of creating a more desirable, less dense surface environment by creating more open spaces and outdoor recreational facilities and parks. Deeper tunnels can be placed beneath existing urban areas for public services such as transportation, water conveyance, or utilities with minimal disruption of the surface. The concept of using utility corridors in which all utilities are placed in a tunnel under the city streets is widely desired and has great advantages.

The use of the underground space provides isolation of the facilities from the elements. Thermal isolation is naturally provided by the ground with a uniform and moderate level throughout the year. These conditions offer protection against extreme climates and are suitable for those spaces that should be in moderate and constant temperature and humidity conditions such as food storages and document archives. The isolation benefits reduce the needs for climate control and its associated costs and environmental impacts. Furthermore, the containment function of the ground offers protection of the surface from potentially hazardous and undesirable materials stored underground such as the storage of hazardous materials or nuclear waste. Also the containment function of the ground protect the environment and the population from exposure to radiation or other hazardous by-products of processes and experiments conducted in high energy research facilities.
Natural disasters such as hurricanes, tornadoes, thunderstorms and flood have lesser impact on underground spaces because they are protected from the elements. Furthermore, earthquakes affect far less underground structures than above ground structures. The structural oscillation and amplification effects for underground structures are limited, since they are constrained to movement of the ground.

Finally, the use of underground space will provide additional environmental benefits in term of visual benefits, air quality by removing vehicles from streets, and a reduction of noise and vibration. None aesthetically pleasing facilities can be hidden underground, services such as utilities and transportation can be placed in tunnels allowing for better air quality, lesser noise, less congestion and better quality of life at the surface. The use of the underground facilities has a lesser impact on the local and global ecological cycle.

3. **Historical Use of the Underground Space**

   What is considered unconventional use of the underground space today was the normal use in ancient time. Underground spaces has been created and used throughout human existence from dwelling in caves to the use of underground for storage and protection. Since ancient times people found in grotto protection from predators and climatic conditions. First humans lived in natural caves, with the development of tools and techniques they built or enlarged natural caves or openings to provide the needed protection. In 4000 B.C. inhabitants of the Banpo site (China) lived in semi underground pit dwellings. During the Bronze Age (2700 B.C.) the inhabitants of what is now Khirbet Ez-Zeiraqoun in Jordan built a water tunnel system 100 m deep. See Figure 2. Underground chambers and tunnels used during the Jewish revolt against the Romans nearly 2,000 years ago have been uncovered recently in northern Israel. In 2nd century, the Christian community in Rome, started to dwell in catacombs (underground burial places) under Rome for protection and safety. Catacombs can be also found in Naples, and Paris. Naples's catacombs are dated back to the 3rd century while the Catacombs of Paris, the “Municipal Ossuary”, is a network of more than 300 km dated back to the end of 18th century.

   The Cappadocia region in Anatolia, Turkey contains as many as 200 underground cities, probably used since the Bronze Age for protection, and then as settlement in the Byzantine period in the 5th century. Cappadocia is a central region of Turkey, characterized by a soft volcanic tuff that enabled the inhabitants to build underground settlements. Its first inhabitants of the Bronze Age have excavated deep cavities for protection and to escape from the attacks of wild animals and to provide shelter of the hard winter conditions. Later in the 2nd Century these cavities were enlarged and connected with tunnels and labyrinths to be hiding places of the first Christians escaping from the persecutions. During the Byzantine period in the 5th Century underground houses, churches, chapels and monasteries were created. In the underground cities of Cappadocia there are dwellings, storage areas, stables, wineries, mill stones and even graves. Shafts for ventilation and communication run between the floors, and huge stone doors blocked off the tunnels in time of danger. Figure 3 shows Kaymakli, one of the Cappadocia underground cities.

4. **Development of Current Unconventional uses of the Underground Space**

   Nowadays underground spaces are used mostly for different purposes than what they were historically used for. Today most of the underground use is for transportation including vehicular, rail, transit, and pedestrian tunnels; for conveyance of water including fresh and waste water; for distribution of utilities such as power, communications, fibre optic cables; for storage of hazardous or contaminated materials; and for military installation and defence facilities. Even in the traditional uses of tunnels and underground spaces, there are opportunities to apply non traditional uses as can be seen herein.

4.1 **Transportation**

   The use of road and rail tunnels is common and expected when crossing mountains or waterways. Similarly in urban areas rapid transit systems are placed underground. Even sometimes pedestrian crossings or passages are built underground. However, other uncommon underground transportation mode is the use of underground canals. During the Industrial Revolution in the late 18th Century and early 19th Century, many underground canals were built throughout Europe mainly to transport coal and manufactured products by barges. The longest of such canals is the “Worsley
Navigable Levels” in Lancashire County and Manchester, England. It was built in 1776 to transport coal. It is 52 km long excavated in hard rock. Another example is The Standedge canal tunnel in England. It is 5 km long, 194 metres underground at the deepest point, and 196 metres above sea level. It was recently renovated and reopened for recreational use. Figure 4 shows the entrance to the canal tunnel at Marsden. A recent example of canal tunnel or ship tunnel is the planning of the Stad ship tunnel in western Norway to insure a safer route for ship traffic along the North Sea coast. It is 1,700 m long, 23 m wide and 45 m high. The tunnel will cut through a peninsula saving ships the risky journey around the coastline and saving time and operating cost. Figure 5 shows an illustration of the ship tunnel cross section. Furthermore underground subway or rail stations can serve as focal points for development of commercial centers and provide opportunities for underground connections to surrounding commercial and institutional buildings. In cities such as Montreal, Toronto, Tokyo, and Paris, the subway stations are part of large underground shopping centers and pedestrian networks.

4.2 Residential Uses

Residential uses are the oldest use of underground space by humankind as illustrated by the numerous examples above. However, such use is not limited to historical perspective only. It is estimated that over 30 million people live in some sort of underground structures in China today. Similarly in the early 20th Century, it was estimated that 20,000 people in France live in some sort of underground dwelling. Many other countries and regions can point to at least a few examples of historical or present day uses of underground dwellings. The principal drivers for underground use appear to be the climate, topography, the availability of inexpensive building materials, the availability of a suitable geology, landscape, and for environmental benefits in the case of modern underground dwellings.

Recently, there has been renewed interest for fully or partially underground dwellings or earth sheltered homes. Again the main reasons for the revival of underground dwelling are environmental benefits, sustainability aspects, geothermal insulation properties, and reduction of energy consumptions. Many architectural designs provide residents of earth sheltered homes or underground homes with the full amenities and comfort as in any other home. Figure 6 shows examples of modern residential underground homes.

4.3 Recreational Facilities

Modern recreational facilities have been constructed underground include sports facilities, theatres, concert halls, and community centers. Many such facilities have been constructed in Scandinavia and serve dual-purpose for recreational and to be available for civil defence as shelters. The types of facilities in use include swimming pools, gymnasia, running tracks, ice hockey rinks, and multipurpose facilities. An example is the Hervanta swimming pool in the suburbs of Tampere, Finland, located 30 meter underground. It occupies the underground space of an anti-atomic shelter. Another example is the Gjøvik underground Olympic hall in Norway. It is the largest underground multiuse recreational cavern in the world. It is 91 m long by 61 m wide and 25 high and has a seating capacity of 5,100 people. It was constructed for Lillehammer's XVII Olympic Winter Games in 1994. Figure 7 shows two examples of underground recreational facilities. Other recreational facilities built underground includes movie theatres, tennis courts, ice rinks, and other similar facilities.
4.4 Institutional Facilities

Many institutional facilities such as libraries, schools, museums, churches, and concert halls are being constructed underground for various reasons including aesthetic, availability of space, environmental benefits, thermal insulation, noise and vibration reduction, and cost. For example, the Civil and Mineral Engineering Building at the University of Minnesota, was built underground in response to the lack of open space on campus, to meet the harsh winter climate, and to satisfy energy-efficient standards. However it was also a demonstration of the potential for the development of mined spaces in the Minneapolis-St. Paul geology. More than 95% of the building is in four underground levels with the lowest level at 33 m below the surface.

Placing libraries underground is better suited for document preservation, protection, and security. The underground space provides the ability to accurately and constantly have a better climate control within the library and document storage areas at lower cost. Book vaults, stacks, and special collections can be better kept by being in a more secure and better environmentally controlled place. There are many excellent examples of underground libraries. Some notable ones are the Nathan Marsh Pusey Library in Harvard University; the Radcliffe Science Library at Oxford University; and the seven-story deep addition to the National Diet Library in Tokyo. Other examples are the National Archives in Stockholm which consists of two large underground depositories built into the bedrock; and the recent addition to the Morgan Library in New York to house a new performance hall and an expanded space for collections. Presently under construction is the Mansueto Library in the University of Chicago. It will take the form of a glass dome rising about 10 m above the surface, while the majority of the library is underground. Figure 8 shows a cross section of the Mansueto Library and the work under construction. Another class of institutional facility is the visitor centers for an important historical or natural site. The building is often placed underground to allow the site to remain the focus of attention.

Unusual institutional facilities that were built underground include prisons, and churches. The Minnesota Correctional Facility at Oak Park Heights was built into the side of a hill with the exterior walls almost completely below the surrounding grade level. Security is maintained without the visually imposing high perimeter walls and watch towers.
The Temppeliaukio Kirkko (Church of the Rock) in Finland is built entirely underground in a natural granite outcrop (figure 9). The church is circular with exposed rock walls.

4.5 Commercial Complexes

Many commercial buildings and shopping centers are placed underground for aesthetic, protection of the harsh weather of the customers, and concerns and preservation of open space above ground. Many of the commercial centers are placed underground in the city center because of lack of above ground space and to relieve congestion of buildings and traffic. One of the largest examples of an underground commercial complex connected to urban transit is the redevelopment of the Les Halles site in Paris. The complex covers 100,000 m² on the surface and extends four levels below grade while preserving most of the surface as a park surrounded by historic structures. Les Halles is notable for the diversity of systems and uses it contains. These include a subway station, roadways, car parking facilities, a shopping center, and community and recreational facilities including a swimming pool. The complex is a perfect model of enhancing the total human environment by utilizing underground space. Another major underground center, and claimed to be the largest in the world, is RÉSO or La Ville Souterraine in Montreal, Canada. See Figure 10. RÉSO is a set of interconnected underground complexes. Its tunnels consist of a network of 29 km, spread over an area of 12 square kilometres. They provide weather protected access to ten subway stations, two railway stations, two bus terminals, two universities, several major hotels, numerous commercial businesses, many department stores and boutiques, restaurants, banks, movie theatres, two exhibition halls, and 10,000 indoor public parking spaces. With its pedestrian corridors, shopping promenades, and direct access to several surface structures, it is considered an underground city.

Japan has had a long history of development of underground urban shopping centers. Two enormous underground shopping complexes were built adjacent to subway and rail stations in Osaka in 1957. They were designed to relieve pedestrian traffic on Osaka's crowded streets and quickly became profitable ventures. After numerous expansions, now covering more than 127,000 m² and include over 1,000 shops and restaurants. The immense land pressures in major Japanese cities and the high land prices are spurring interest in more commercial underground uses as well as infrastructure service uses. More than 20 Japanese cities now have underground shopping complexes with connections to subway lines. Similarly major underground commercial centers with connections to underground transportation systems are being developed in China. Examples include the Shanghai Expo 2010 which includes 400,000 m² of underground facilities and showrooms; and the planned underground city of the core district of Qianjiang New City in Hangzhou with a total underground space of 2 million m².

4.6 Storage Facilities

Storage of food underground dates back to early civilization. Underground food storage has historically been done for food preservation, rodent and insect control, and preservation of food supply against pilferage or attack by invaders. Major historical examples include the underground grain silos discovered in Luoyang, China, dating from the Sui and Tang Dynasties (6th and 7th centuries).

Today, underground storage is common for many products including coal, oil, natural gas, LNG, compressed air, document storage, hazardous and contaminated materials including nuclear waste, etc... Oil and gas are critical elements in the fuel supply of industrialized countries, both economically and militarily. To protect the needs from seasonal supply problems, international shortages, or acts of aggression, a large number of oil and gas storage facilities have been constructed underground. Many of the largest storage facilities have been constructed underground due principally to higher security, lower cost, and reduced potential of environmental impact. Cavern excavation and/or solution mining were used to develop oil and gas storage caverns. A major example is The US Department of Energy's Strategic Petroleum Reserve. It was established to develop government-owned crude oil reserves, thereby reducing the impact of interruptions in oil supplies. It is the largest...
emergency stockpile of crude oil in the world. It was mainly excavated by solution mining of salt domes. Figure 11 shows a schematic of solution mining of a salt dome for oil storage. The Scandinavians developed the use of unlined rock caverns below water table for storing oil. The oil floats on the water bed and is contained by the depressed surface of the groundwater around the cavern. Recharge systems were later developed to allow storage above the natural groundwater level by controlled water injection to create an artificial containment. Oil can also be stored in abandoned mines, but layout and flow often present difficulties for such use. Natural gas, liquefied gas, and Carbon Dioxide (CO2) may be stored in underground pressurized storage utilizing either caverns or the natural pore space in a porous rock layer, and are situated at such depth that the water pressure and/or rock confinement is sufficient to confine the natural or petroleum gas at the storage pressure and temperature desired. Figure 12 shows options for underground storage of CO2.

Nuclear waste storage is one of the most controversial issues in the nuclear power industry. The storage of spent fuel is a major concern for many industrial countries with nuclear power. Where to store it and how to transport it? Are questions that raise a lot of discussions and debates among scientists, engineers, environmentalists, common people, and politicians. Nuclear waste can be stored safely in deep geological disposal sites in underground formations that are inert with no impact on groundwater or seismic hazards or potential contamination of the environment. A recent location established for placement of radioactive waste in the United States has been Yucca Mountain in Nevada. The repository was under construction and would have placed the nuclear waste about 500 m underground. Unfortunately the project lost funding last year. Figure 13 shows a schematic of Yucca Mountain disposal site. Other industrialized countries have developed underground storage facilities for low level and high level nuclear waste.

Secure storage of archival records and essential documents for continued functioning of government and businesses in case of a natural disaster or act of war is critical. A series of facilities have been developed around the world to provide a maximum level of security. In the U.S, for example, records of the Mormon religion are kept in a deep underground chamber near Salt Lake City, Utah. The Norwegian national archives are now located in a shock-protected building constructed within a rock cavern. Many government offices and businesses not only store records but also duplicate computer systems and records that would permit virtually uninterrupted operation after a disaster.

Some other underground storage that has been in existence for thousands of years and continues to be used are wine cellars and cheese storage facilities. Wine cellars are a traditional underground use that is regaining popularity. The use of caverns for aging wine has been in continuous use in many wine-producing regions such as France and Italy. In newer wine producing regions such as California which did not have the traditional caves, new facilities are being excavated underground in caverns to provide a cost-effective alternative to climate-controlled surface wine aging warehouses.

A recently completed project of unusual storage facility is the Svalbard Global Seed Vault in Norway. It was created to store a large portion of the world’s natural seed lines, with capacity for 4.5 million varieties totalling over 2.25 billion seeds. The location and design of the Svalbard facility allows it to retain seeds at a long term temperature of no more than -3.5°C (27°F), so that in the event of the loss of a seed line does occur due to natural disaster, drought, war, or, other circumstances, crop types will not be lost. Figure 14 shows the Svalbard Global Seed Vault.

Other underground usage includes military installations, experimental facilities, civil defence facilities, industrial facilities,
5. Conclusion

The underground space is the new frontier; numerous benefits can be obtained by considering the potential unconventional uses of the underground. It can be used to relieve congestion; provide connections of people and neighbourhoods; protect residents from noise, poor air quality; reduce overbuild and crowding; and accommodate more open and green spaces on the surface. Its use enhances sustainable developments and improves the environment at large. Development of underground facilities is cost effective considering the life of the facility and the opportunities of using abandoned underground facilities such as mines or old military and civil defence installations. The life expectancy of a tunnel or an underground structure is much longer than a surface facility because of its protection by the surrounding ground. The useful life of a tunnel or an underground structure is 100 to 150 years while above surface facilities expected life is 50 to 75 years. Furthermore, the opportunity of air rights developments over a tunnel or an underground structure is often missed when performing comparative cost evaluation. Underground space development should be part of the city planning and following the context of an existing urban plan. It should be properly coordinated with and reflect the surface plan. With the predicted population growth and the growth of megacities, efficient use underground space promotes sustainable development, improves urban environment, preserves natural resources, and accomplish long term financial benefits.

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