


Planning and Designing Successful Underground Facilities:

A summary of lessons learned from worldwide projects



Raymond Sterling and Surbana Jurong Consultants








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Surbana Jurong

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SJ Underground Development is part of the Surbana Jurong Group and we specialized in planning, designing and managing projects related to underground infrastructure projects such as metro, roadway, utility tunnels and underground caverns. We focus on providing specialist geotechnical, civil and structural engineering consultancy services for major temporary and permanent works. Our technical expertise includes bored tunnels, mined tunnels, cut-and-cover tunnels, metro stations, shafts, pipe-jacking, micro-tunnelling, rock caverns and related impact assessment of adjacent structures/utilities due to underground construction works.

Some notable innovative projects that the team has undertaken include the design of a pedestrian underground tunnel in the heart of Singapore’s Civic District, adopting the “Rectangular Tunnel Boring Machine” method of construction; and also shaft design, adopting the “Vertical Shaft Sinking Machine” method of construction in the second phase of Singapore’s Deep Tunnel Sewerage System Project. This advanced technology for shaft construction works is a first in Asia.

Acknowledgments

Collecting and presenting “lessons learned” from underground facilities built several decades ago and scattered around the world was a challenging task extending over approximately 18 months. It was made possible, however, by the willingness of owners, managers, operators, planners, architects and engineers to take the time to share their experiences with their facility. Specific individuals contributing to the study are listed at the end of this document but there are others who also contributed but are not acknowledged individually. In addition, due to language barriers and distances involved for some of the case studies, the contact was made through a colleague or colleagues in that country who could serve as liaison(s) between the facility owners and myself. Here, I would simply like to add a collective thanks and acknowledgment to everyone who made this study possible.

While the major responsibility for collecting, analyzing and presenting the information in this study rested with myself, it could not have been undertaken or completed effectively without the support of Surbana Jurong Consultants Pte Ltd, Singapore. The company decided to provide both financial support for the study and participation by some of its key engineering personnel who accompanied me on a number of the facility visits during the data collection process and helped in the discussion and presentation of the study findings. I would like to particularly highlight the contributions of Thomas Tang, Richard Ting and Clayton Wong in this regard.

Raymond Sterling

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1. Introduction

For thousands of years, underground spaces have been used by humans for various purposes: shelter, storage, water, sanitation, transportation, etc. as well as being created as a by-product of mining operations. Most early uses were responses to specific geological opportunities, security concerns and/or climate adaptations. However, in the past century or so, the use of underground space has emerged as a broader means of supporting the infrastructure and space needs of the rapidly increasing world population – particularly in major cities.

Singapore is a strong example of the issues being faced – a growing economy and population plus a desire for a liveable, attractive and dynamic environment – all constrained by a small land area. In response to these concerns, the Singapore Government has for the past 2-3 decades been studying and planning for using underground space to a significantly increased degree. Such use allows the moving of “bad neighbour” facilities from the surface environment, provides space for the unobtrusive provision of the essential infrastructure facilities that modern cities require, and in general provides a new “land bank” to supplement the dwindling possibilities for offshore land reclamation.

Singapore is in the early stages of this development compared to the older urban areas of the world. It has and is continuing to build extensive underground utility and transportation infrastructure and the coming years will see a massive increase in the number of underground facilities being constructed and in the variety of uses to which they will be put.

Moving facilities underground is not without its disadvantages and detractors. The construction cost of underground facilities is typically higher than for surface facilities and when land costs and environmental impacts are not included in the evaluation, they can seem an expensive alternative to a surface solution. In broader terms, though, there are concerns that moving more than service facilities underground could create undesirable working and living environments for significant sectors of the population. Such concerns are likely to become more widely expressed as the range of underground facilities grows. There are also particular design and specification issues for underground facilities to deal with problems not so critical for aboveground facility designers (e.g. waterproofing).

The idea that Singapore and other cities/regions of the world are poised to greatly increase their use of underground space and that there are a variety of underground facilities around the world that now have several decades of operating experience led to the development of this study. The study also built on two previous efforts to look at lessons learned from a small set of underground buildings (Sterling and Carmody 1991 and Sterling 2017).

Over an approximately 18-month period in 2019 and 2020, the study has gathered information on 42 underground facilities worldwide that have a long-term history of use and operation – allowing a collection of the lessons learned from such underground facilities as they have progressed through their years of service and with a focus on those planning, design, construction and operational aspects that have special significance for underground facilities. In essence, this study was intended to be a form of post-occupancy evaluation for a facility but one done after years of service instead of shortly after occupation.

Particular attention was given in the study to examples of human occupancy uses worldwide and less attention was given to underground infrastructure uses such as road and rail tunnels. Passenger acceptance of underground metro systems can be an important issue but this topic already receives significant study and hence only one example of metro station design was included.

The case studies included were grouped into 9 categories of use for ease of comparison among the facility experiences. The categories of use and the individual case studies included are:

- **Libraries, archives and museums:** Pusey Library, Harvard University, USA (44); Hennepin County Library – Walker, USA (31*); Archives of the National Library of Sweden, Stockholm (23); Oya History Museum, Oya, Japan (41); Leros War Museum Tunnel, Greece (16); Vagonetto, Fokis Mining Park, Greece (17); Takayama Festival Float Art Museum, Japan (22); Quran Museum, Tehran, Iran (43); and Azadi Tower Museum, Tehran, Iran (49).
- **Sports facilities and community centers:** Gjøvik Swimming Pool, Norway (45); Gjøvik Olympic Ice Hockey Arena, Norway (27); Holmlia Sports Center, Norway (37); and Osaka Municipal Central Gymnasium, Japan (24).
- **Underground shopping and pedestrian complexes:** Pedestrian System (RESO), Montréal, Canada (58); Azalea Mall, Kawasaki, Japan (34); Nagoya Station Shopping Network, Japan (~54); Xinjiekou Center, Nanjing, China (15); and Taipei City Mall (20).
- **Transportation, intermodal and commercial developments:** Stockholm Metro, Sweden (75); Forum Les Halles, Paris (41); La Défense, Paris (42); and Shanghai People's Square Underground Space (~30).
- **Underground parking facilities:** EuroPark P-City Forum Complex, Helsinki (24); and Automated Parking Cavern Reuse, Qingdao, China (~50).
- **Research facilities in universities and industry:** Civil Engineering Building, University of Minnesota, USA (37); Hagerbach Test Gallery, Switzerland (51); ZaB – Zentrum am Berg, Austria (13); and Underground Research Facility, Aalto University, Helsinki (~50).
- **Educational, office and service uses:** Mutual of Omaha Headquarters Building 4, USA (41); CA Employment Devel. Dept. (EDD) Subterranean Annex (38); Williamson Hall, University of Minnesota, USA (43); ArtEZ School, Arnhem, The Netherlands (16); and Wildwood School, Aspen, Colorado (46).
- **Industrial and storage uses:** Meritex Lenexa Executive Park, Kansas, USA (31); Diplom-Is Ice Cream Storage Facility, Oslo (~40); Finnish Red Cross Blood Service Storage (SPR), Helsinki (35); Henriksdal Sewage Treatment Plant, Stockholm (~85); Stanley Sewage Treatment Works, Hong Kong (25); and Isséane Waste-to-Energy Plant, Paris (13).
- **Special uses:** Temppeliaukio Church, Helsinki (51); Sonoma and Napa Valley Wine Caves, California (33); and Caer Llan Centre Berm House, Wales (33).

The figure in brackets after each case study is the facility age in 2020. An asterisk next to the age indicates that the facility was closed at the age shown and the ~ indicates either an approximate age or the average age of several facilities. Both the average and the median length of service for the 42 facilities included was approximately 37-38 years.

There were challenges in conducting the study – mainly relating to the length of time that had elapsed since facility planning and design and the time burden and accessibility of information for the current personnel to collect and transfer and make available the information on their facility. The wide range of types of facilities included also introduced problems with having a unified questionnaire to elicit the desired information.

Figure 1. Geographical distribution of case studies (created using Google Maps)

2. Organization of Findings

There are many technical design manuals for underground facilities and several examples of more broad ranging guidance that include information on the planning of underground projects and their architectural design (e.g. Admiraal and Cornaro 2018; Carmody and Sterling 1983, 1993; Hall 2004; van der Hoeven 2016; ITA 2012; Labbé 2016; Mangin 2016; von Meijenfeldt 2003; Perrault 2016 and Reynolds 2020).

What this summary attempts to do is to put the experience from the 42 case studies investigated into a general framework of the various planning, design and technical decisions that are made when designing an underground project – with an emphasis on the design of underground facilities in terms of their acceptability for purpose by the users of the facility and acceptability as a work environment for the people that are employed there.

The discussion of the lessons learned are organized by the various stages of planning, design, construction and use and then subdivided by the types of factors that either have been suggested as important in existing design guidance or have proved to be important from the case studies. The people-related issues and design patterns suggested in Carmody and Sterling (1993) are used as an organizational framework.

3. Planning and Decision Making

In reviewing the decision making issues for the case study examples, the case studies are grouped into various types of facility and, since all the case studies involved decisions to build underground, this section can also serve as a brief introduction to each of the case studies.

3.1 Libraries, Archives and Museums

In this category, an aboveground building would normally be the choice without constraining issues – particularly for libraries where natural light, visibility to patrons and easy access are important. For museums, which typically have many windowless spaces, an underground choice is an easier one to make but is still affected by relatively higher construction costs and the ability to create a stronger image with an aboveground building. For an archive facility, it is all about convenience, logistics and cost since the facility is essentially a warehousing space.

There are two libraries and one archive facility included in this study. The Pusey Library was placed underground to preserve an important open space on the Harvard University campus and the decision is still considered a wise one and the building is well-liked over 40 years later. The Walker Library was placed underground on a small urban site – partly because this would allow parking on the roof and save the acquisition of additional land that would be required for a typical aboveground library design and partly to take advantage of several of the other characteristics of underground buildings. The ideas were persuasive enough at the time for the underground library to be built but a variety of building and operational issues detracted from its effectiveness. These problems, coupled with a generally poor reception by staff and patrons, led to its replacement with an aboveground library on the same site after 31 years of service.

Figure 2 Central courtyard of the Pusey library at Harvard University (courtesy Harvard U.)

The archive facility among the case studies is the Archives of the National Library of Sweden. The library itself was situated in a monumental building surrounded by a park in the center of Stockholm. The choices for archive space were surface warehousing at some distance from the main library or a rock cavern archive space beneath and directly connected to the library. The choice for the main collection of books and print materials including the historic collections was to keep it integrated with the main library location. This is still considered to have been a wise choice.

There are six museum facilities included. Three of these facilities are underground museums created to showcase the underground space itself: the Oya Stone Museum, the Leros War Museum and the Vagonetto Mining Park. For these types of facility, the planning decisions were more about whether to create a museum or not and to what extent the museum would mix surface facilities with the use of the existing underground spaces. All three museums are still seen to fulfill a valuable role in preserving their aspect of history and the Oya Museum provides access to some dramatic rock-cut spaces.

Figure 3. Entry courtyard, Quran Museum, Tehran (courtesy: Dr. Mohammad Mahdi Safaee, Islamic Azad University)

The other three museums are the Takayama Float Festival Museum in Japan, the Quran Museum in Iran and the Azadi Tower Museum, also in Iran. The Takayama Museum was created in a large newly-constructed rock cavern to store and display the national heritage of festival floats. It was funded by a wealthy benefactor involved in the preservation of the float craftsmanship and solved a siting problem for such a large museum in a hilly district. The Quran Museum was a replacement use for an underground building designed as a cultural center for the historic district in the center of Tehran. The Azadi Tower Museum was combined with visitor facilities and set below ground to preserve the view of the symbolic landmark of the tower. All three uses were well suited to the choice for siting underground and preservation of surface views was important in each of these cases.

3.2 Sports Facilities and Community Centers

This has been a common type of underground facility in Scandinavia where, in the 1970s and 1980s, many such facilities were built in rock caverns with a dual use as civil defense or emergency shelters. The three facilities of this type included in this study are: the Gjøvik Swimming Pool, the Gjøvik Olympic Ice Hockey Arena and the Holmlia Sports Centre.

Figure 4. Gjøvik pool (initial configuration) (Courtesy E. Broch)

The emergency shelter role was an important aspect in the underground siting of these facilities in rock caverns. It was necessary for the level of blast protection required. To assist with the cost of the additional civil defense measures and to provide support for the shelter creation, financial support was available for the early caverns. This support and the requirement to build shelters was discontinued in Norway after the end of the Cold War although the requirement for shelters continues in Finland. The primary aspect for the facilities, however, was to create a useful community facility and, in the hilly/mountainous topography of Norway such facilities were typically difficult to site aboveground in convenient locations near the center of the community.

In all three Norwegian examples, the facilities have performed their functions well. The Gjøvik pool and the Holmlia pool and sports facilities have been very accessible for the communities and well used and liked. The Gjøvik ice hockey arena provided a dramatic venue for the 1994 Winter Olympics and showcased Norwegian expertise in building what remains by far the largest span rock cavern for public use. However, the rural setting of the large arena has limited its ongoing commercial success.

The fourth sports facility included in the study was an earth-covered sports arena in Osaka, Japan. The decision to build the facility in this way was necessitated by the decision to build within an existing city park. This was not permitted unless the building would occupy less than 2% of the park surface. Keeping the new sports arena near the center of the city was important to the city and land costs and land availability would have been prohibitive if the park site were not chosen.

3.3 Underground Shopping and Pedestrian Complexes

This category overlaps somewhat with the category "Transportation, Intermodal and Commercial Developments" that follows but the current category concentrates on discrete underground shopping centers that are connected to transportation hubs as well as extended city/district-wide pedestrian networks that link many buildings.

The examples included in this section are: the Montréal underground pedestrian network in Canada, the Azalea underground shopping center in Kawasaki, Japan, three of the nine underground shopping centers at Nagoya Station in Japan, the Xinjiekou underground pedestrian network in Nanjing, China and the Taipei City Mall.

The decision making involved for these kinds of networks typically revolves around several key considerations:

- The need to separate pedestrians and traffic in downtown areas and around transit and train stations to smooth traffic flow and increase pedestrian safety

- A decision between a grade-separated pedestrian network aboveground (skyway) or belowground
- The need for additional shopping in the area for which there is no space aboveground
- The commercial opportunity offered by large pedestrian traffic flows
- The combination with underground parking levels beneath the shopping.

For all of these networks, the safer and less disruptive distribution of pedestrians around train and metro stations was an important consideration. Underground networks were chosen either because they connected more easily to the underground metro systems or because skyway connections were blocked by existing overhead roads or rail. Underground parking was combined with several of the underground shopping malls.

Important lessons learned in terms of decision making are:

- The financial and legal framework for the expansion of pedestrian networks affects the ability of the city to guide the simplicity of the network for its users (Montréal and Nagoya)
- Where pedestrian volumes are high, shops can be successful even if the nature/usage of the shops needs to change over time
- Parking needs have changed over time – either due to installation of parking elsewhere, lower use of cars in the city, or change in the usage of types of transport (e.g. more two-wheeled vehicles).

Figure 5. Underground pedestrian network in Montréal (photo: R. Sterling)

All the above networks have been successful and continue to be so but they have had to be willing to adapt and update to keep their offerings current and manage emerging issues such as wayfinding and flood prevention as the networks get more complex or environmental conditions change over time.

3.4 Transportation, Intermodal and Commercial Developments

Three complexes and a transportation system are included in this category of use. The principal differences from the previous category are looking at the issues when transportation and pedestrian areas are combined in a single complex or understanding the design evolution of a city's underground transportation system. Included is the Stockholm Metro (which has a special history related to station design and its public appreciation), the Forum Les Halles complex in Paris which has combined multiple transportation modes with a large shopping and community center in a single underground development, the La Défense elevated slab district which has created a massive business district interconnected by an elevated pedestrian plaza and underground transportation, and the Shanghai People's Square Complex that has preserved open space in the center of Shanghai while providing traffic-free pedestrian connections among three metro lines and multiple buildings.

The planning and design approach for each of these projects was carried out more than 40 years ago and significant evolution in needs has occurred in the decades since then. Some cross-cutting issues are:

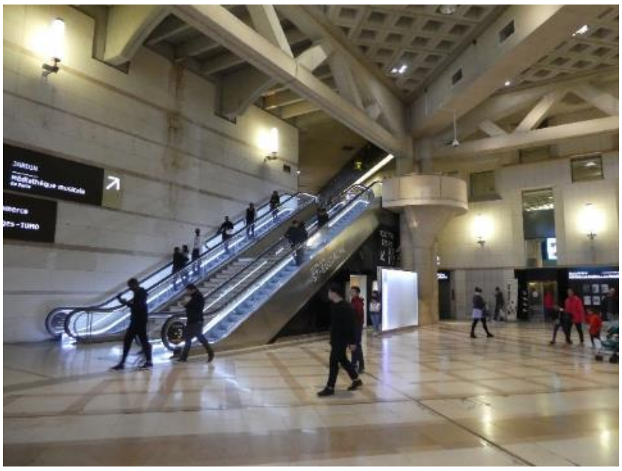

Figure 6. Forum Les Halles, Paris (photo : R. Sterling)

- Major public projects in city centers are visible public projects and attract a lot of comments and criticism. They also take a long time to plan and construct – making decision making difficult and apt to change over time with changes in political administrations (Les Halles, La Défense)
- Changes in technical requirements such as ventilation and fire safety can strongly affect the layout and aesthetics of the underground spaces (Stockholm, Les Halles)
- Underground spaces that are not part of the main pedestrian flows from stations or to other destinations can be vulnerable to changes in shopper behavior (e.g. online shopping) and this may be difficult to overcome (e.g. Shanghai Dimei Mall).

Stockholm is in the early stages of a major expansion of its metro system to increase capacity and relieve pressure on its existing system. At present, during rush hours, the experience of the dramatic rock cavern stations is obscured somewhat by the crowded conditions. For the future stations, the changes in technical requirements make exposed rock cavern stations unrealistic but the commitment to artist involvement and striking design remains.

A very effective transportation and commercial “engine” in the center of Paris, Les Halles has just completed a major renovation project incorporating a massive new “Canopy” to cover the central station area. Much has been done but criticisms still remain – showing both how difficult it is to renew a massive intermodal and commercial development that must remain open every day during the reconstruction and how difficult it is to radically change geometries that are fixed by major transportation facilities.

La Défense also is very successful as a business district and has a strategy for pedestrian-traffic conflict that appears simple and effective: build a raised pedestrian slab for the people and put all the service functions beneath – out of sight and, for many functions, without the expense of digging them into the ground. Some of the key dilemmas that have evolved over the years in La Défense are that:

- The voids created aboveground but beneath the slab are used by people arriving by bus, taxi or car but were left more or less unfinished giving a very poor impression for the major business center.
- The accessibility of the below-slab spaces provides a variety of security and homeless issues to be dealt with – adding to the negative impression above.
- Little attempt was made to plan for the use of any left-over spaces. However, given the financial success of La Défense, such useful space could be made valuable.
- The pedestrian slab at La Défense is typically 12m above the surrounding ground level and has a road system surrounding its edge. Hence, it has a poor natural connection to the surrounding neighborhood except at certain access points.

These issues have been recognized and acted on for more than a decade but, as for Les Halles, it is difficult to alter some main geometric, functional and structural elements of the original design.

For the Shanghai People's Square Complex, the main ideas behind its creation have remained valid and the preservation of the open space at People's Square is a real asset. The complex has had to respond to a flooding event from the increasingly heavy rains that are occurring and the Dimei Underground Shopping Mall that is connected to the complex has seen significant store closures due to the increase in online shopping and despite a recent remodeling. The number of people using the underground system to access the metro and surrounding buildings means that the complex remains critically important for this central area in Shanghai.

3.5 Underground Parking Facilities

Two parking facilities were included in this category. One is a very large set of parking caverns (P-City Forum) excavated beneath the center of Helsinki, Finland and the other is interesting as a reuse of obsolete civil defense caverns to provide an automated parking facility beneath a hospital in Qingdao, China.

Figure 7. EuroPark P-City Forum parking in Helsinki (photo: R. Sterling)

In Helsinki, the parking caverns have two levels of parking and three widely separated vehicular entrance/exits. With 13 pedestrian connections to different locations and buildings in the city center, it is possible to conveniently park close to a downtown destination. The parking facility is a commercial business but also serves as an emergency shelter for the downtown area. After a slow start (thought to be due to concerns about underground wayfinding by car and on foot), the facility is well used, is a good business, and serves the city center well.

The Qingdao parking facility has just started operation but the original civil defense caverns were built in the 1960s – but without an ongoing usage for non-emergency periods. The caverns were later determined as not meeting updated civil defense standards and the caverns were quite neglected for a long period of time – resulting in significant deterioration of the condition of the caverns and their internal facilities. In 2016, a proposal was made to use the cavern space to meet a critical shortage of parking spaces in the area of the main hospital in Qingdao. The caverns were refurbished and the main cavern enlarged to accommodate an automated parking system. The new facility was finished and opened for a period of testing in 2019. The lessons learned in terms of decision making for underground facilities reinforce the need for emergency facilities to have a valid ongoing purpose so that the facilities are familiar to those who will use them and so that the facility remains maintained. The project also has demonstrated the increased difficulty of reconstructing or renovating existing underground spaces through relatively small access points that are now in the middle of busy commercial areas.

3.6 Underground Research Facilities

Four research-oriented facilities were included in the case studies. The Civil Engineering Building at the University of Minnesota is a University departmental building with both teaching and research functions. It is unusual because it combines a cut-and-cover building with mined space below and it was conceived as a land-saving and energy conserving demonstration building for the campus. The other three facilities all utilize rock tunnels and caverns for research, education and training purposes. The Hagerbach facility in Switzerland has created underground spaces for various types of underground construction and underground space use research allowing it to offer technical support, testing and training to a variety of industrial partners and government agencies. A more recent facility, the ZaB – Centrum am Berg facility in Austria has a somewhat similar function and was developed using tunnels from an existing mine combined with newly constructed spaces. A much smaller facility is the Underground Research Facility at Aalto University in Finland. This serves the Aalto University Civil Engineering department and consists of some rock tunnels and chambers that can be accessed from the University's emergency tunnel system. The facility is used for faculty and graduate students doing research in rock mechanics and underground construction and to allow undergraduates and graduate students to be exposed to the techniques used in underground construction.

The planning and decision making for the Hagerbach, ZaB-Centrum am Berg and the Aalto facility all essentially extend or modify their facilities to meet the needs for current research or training. The essential decision was to act to provide a venue to meet the perceived need. The Hagerbach facility created a convenient horizontal portal into a rock hillside that has allowed easy extension of facilities but with a minimal environmental impact. The other two facilities have piggy-backed their facilities onto existing underground works. For the Aalto University facility, the front-line responsibility for maintaining and operating the facility is undertaken by the Department itself. However, the Civil Engineering Building, despite being an unusual building, has a more traditional setup as a university building constructed for the University and managed by the facilities group within the University. With a number of technical problems that have had to be dealt with over the building's nearly 40-year life, various lessons learned about the maintenance of non-traditional building features have been noted. However, all four facilities have an important future role and have validated the decision to create the facilities.

Figure 8. Materials testing area in the Hagerbach Gallery, Switzerland (photo: R. Sterling)

3.7 Educational, Office and Service Uses

This category of case study includes two office building additions: the Mutual of Omaha Headquarters Building addition in Omaha, Nebraska, USA and the California EDD Subterranean Annex in Sacramento, California, USA. Three education-related facilities are also included: Williamson Hall at the University of Minnesota, the ArtEZ School of Dance and Theatre at the ArtEZ University in Arnhem, The Netherlands (a building extension to provide additional education and performance space for the school), and a non-traditional elementary school (Wildwood) designed to instill environmental awareness into pre-school and elementary age children.

For the office building additions, the decision making was quite different in each case.

The Mutual of Omaha addition was designed to add a significant amount of new space to the headquarters building of an insurance company. The image of the headquarters building was well known through the company's support of a popular wildlife television series and, hence, the decision to build underground started with idea to avoid blocking the view of the existing building while adding a new space. Other incentives were the ability to keep the added service functions as close as possible to the existing building and the avoidance of the need to buy new land. After more than 40 years, the original decision is still felt to have been a good one. The building has served well with some relatively minor nuisances and spaces within the addition have been able to be repurposed due to changes in the technologies for records storage.


Figure 9. ArtEZ University, School of Dance and Theatre, The Netherlands (courtesy ArtEZ U.)

The California EDD Subterranean Annex was different in that the addition was designed at the same time as the creation of the six-story office building to which it was connected. The addition was planned as a one-story underground construction to preserve open space on the surface as well as to be an energy conserving structure. The underground addition mostly consists of an open-plan office area accessed from a sunken plaza area. The 38-year-old building gets mixed reviews and has been referred to as near the end of its functional life. In terms of decision making, perhaps the most instructive comments made have been in connection with the fact that the building did not really need to preserve open space in that location and that having a one-story underground building occupy almost an entire city block was not a good land use decision for the center of Sacramento.

Williamson Hall was created with the dual functions of a university bookstore and an admission/records facility. It was one of the early underground buildings across North America that had promoted environmental preservation and low energy use through sinking the building into the ground. The building has had a checkered history in terms of its praise, criticism and technical/design issues. It is now 43 years old and has relatively recently been considered for retirement. It has already changed usage somewhat as the bookstore moved to the main student union building on campus. Was the original decision to build underground a good one? The building design did fulfill many of the things that it had set out to accomplish but some technical and design issues did prove problematic.

The ArtEZ School addition could not have been built adjacent to the existing school building except as an underground building. Building underground allowed the important natural landscape feature of the glacial moraine and river terrace to be preserved and also did not interfere with the view of the existing building which had been designed by the famous Dutch architect, Gerrit Rietveld. The building is significantly younger than most of the other case studies but, so far, the design of the addition has been well received and the decision to build underground to allow proximity to the rest of the school is considered to have been the right one.

The earth-sheltered nature of Wildwood School (not below the surrounding ground level but earth covered and integrated into the surrounding landscape of the Rocky Mountains) came from the desire of the school's founder to create a learning environment for young children that would reinforce an appreciation for nature and instill a desire for enquiry about the natural environment. The building is 46 years old and has had very few problems over its lifetime. The school is fully subscribed with a waiting list to enroll and the building remains attractive and intriguing to adults as well as children. The choice to build the school in this way has proven to be worthwhile.

3.8 Industrial and Storage Uses

The Meritex Lenexa Executive Park is one of 20 plus facilities in the Kansas City region of the USA that reuse space created by a room-and-pillar mining operation to mine limestone aggregate for construction purposes. The ability to reuse such space created through a commercial mining operation means that the underground space is essentially a free by-product of the mining and needs relatively minor additional work to turn the space into suitable facilities for storage, industrial, data center or even office spaces. Care is needed during the mining operation to ensure long-term stability but this is a win-win decision to use existing spaces or develop new mined space for reuse when the geology is found to be suitable and there is also a demand for the mining products.

Figure 10. Entrance to the Meritex mined space reuse in Lenexa, Kansas (photo: R. Sterling)

The Diplom-Is ice cream storage facility in Oslo and the Finnish Red Cross (SPR) blood product storage facility in Helsinki are both examples of storage caverns created in rock adjacent to or below an existing aboveground building to create a secure storage within the existing site. The ice cream storage uses rock cavern space that is cooled to minus 28°C and provides a high degree of security against power failure as well as low operating costs for the facility. Security is also important for the blood product storage but the caverns remain above freezing point and freezer units are installed within the cavern as necessary. With the availability of good rock essentially at the surface and the possibility of low-cost rock excavation in Scandinavia, these facilities both represent good choices that have functioned well and that still provide good value in current operations.

Two sewage treatment plants are included in the case studies: the Henriksdal Sewage Treatment Plant in Stockholm and the Stanley Sewage Treatment Plant in Hong Kong. The original part of the Henriksdal Plant is around 85 years old and it was built underground to save space, preserve the environment, save land costs and, above all, to allow the plant to be built in a logical spot for the sewage collection system. The plant benefits from the constant underground environment (especially in winter) and a large housing complex exists directly above part of the plant. The plant has been expanded several times in the past and is currently undergoing another major expansion. The Stanley plant was built 25 years ago using the Scandinavian examples of rock cavern sewage treatment plants as reference projects. Similar benefits have accrued (except for the cold climate advantages). The success of the Stanley project has made larger relocations of existing sewage treatment plants in Hong Kong to rock caverns possible. Such relocations can free up expensive and desirable shoreline property for other uses – with the land value released exceeding the cost of the relocation.

The Isséane waste-to-energy plant in Paris (along the banks of the Seine) sunk a tall industrial plant into the ground by 31m (102ft) leaving only 21m (69ft) aboveground (including the chimney for the furnace). The exposed portion of the plant was designed to blend in with the business-residential mix in the community. Despite its substantially higher construction cost than a typical aboveground plant, the waste logistics and ease of connection to district heating plus the good location next to the Seine for cooling water and barge transport have made the plant a well-accepted success.

3.9 Special Uses

Three final case studies are listed in this “special uses” category since they do not fit well into the categories already discussed.

The Temppeliaukio Church in Helsinki is a well-known example of a church cut into the rock – partly to save a rocky park area in the center of a residential district and partly for the dramatic architecture that the skylit church with colorful rock walls and copper clad surfaces provides. The decision to build the church underground and its design were very controversial in the beginning but the public reaction when it opened was very positive. It is now the most visited indoor tourist destination in Finland.

Figure 11. Palmaz Winery, California (courtesy Palmaz)

Geological opportunity (volcanic tuff) coupled with environmental restrictions and high land prices have provided the setting for an increasing number of winery facilities to be built underground in the Napa and Sonoma Valleys of California. Although starting with simple tunnels for the aging of wine, many of these facilities now have special underground tasting rooms and event spaces to take advantage of the intriguing atmosphere of a well-designed wine cellar. In the latest evolution, the complete production facilities as well as the visitor facilities have been purpose-built underground at the Palmaz Winery. The low construction costs and the advantages for wine storage make these facilities advantageous even before the land use and environmental benefits are considered.

The final case study is a small earth-covered building project in rural south Wales. It was built to provide additional sleeping space for a field studies center in a steeply-sided valley near Monmouth. Both fitting the project into the space available on the hillside and the desire to make a minimum energy use dwelling structure influenced the design which was prepared by the owner. The result was a building that could maintain reasonably comfortable indoor temperatures with no heating or cooling input throughout the year – a very substantial achievement in the UK climate. The building did have some deficiencies (mainly on the ventilation side) but, with these corrected, the building remains an extremely low energy use building that is an intriguing part of the wedding and event center that is now run at the site.

4. Cost Comparisons

Cost is an important factor in every decision for building a new facility and it can be important when comparing the relative cost of a facility built underground versus a more conventional facility on the surface. Information about cost was sought in the data collection for this study but was quite scattered in terms of the level of detail that could be obtained and also was hard to interpret collectively because of the wide range of uses and geographical locations.

In general terms, the cost implications found from the case studies and the information fall into one or more of the following categories:

- Cost was not a significant issue in decision making for building underground structures/facilities

- Cost was a significant deterrent in decisioning making
- Subsidy assisted cost comparison (e.g. civil defense funding)
- Cost to build underground constrained other aspects of building design
- Underground location offered commercial opportunity
- Ability to reuse existing excavation
- Lower initial cost for underground facility
- Operating cost benefits were substantial.

5. Architectural and Landscape Design

The architectural and landscape design of an underground facility can have a major impact on the user or the public perception of the facility as well as directly in terms of its functional performance. For an underground building, the architect also is typically the lead person who integrates the contributions from the structural, geotechnical, mechanical and electrical engineers as well as other designers such as landscape architects and interior designers. With that lead role, often comes the need to balance competing priorities among the specialties contributing to the overall design, e.g. an impressive overall design versus higher cost for a better waterproofing and drainage system, higher cost for a more capable HVAC system or higher cost for nicer finishes within the building. For cavern facility designs, the engineering and geotechnical role is typically elevated but budget decisions during planning and design remain important issues, e.g. how much to spend on site investigation, whether the facility needs a “dry” interior environment or can manage some leakage with internal drains.

Since many aspects of architectural design do not pertain particularly to underground facilities, the discussion below will describe design issues previously raised as important for underground facilities. One source of such issues is the description of “design patterns” expected to be beneficial in underground facility design that was developed by John Carmody and is presented in Carmody and Sterling (1993). To this set of issues are added a few others that were identified during this study but do not quite fit in the previous organization. The discussion will examine if the case study experiences can reinforce or provide caveats for such design patterns.

5.1 Exterior and entrance design

Design guidance for underground buildings has placed significant attention on the way in which a visitor or user approaches and enters an underground facility. Design objectives identified in Carmody and Sterling (1993) are:

- Clarification of the building’s location and extent
- To avoid the building services becoming the dominant surface expression of the building
- Recognizable entries with variety and complexity and demarcation from adjacent facilities
- Spacious and well lighted entry areas with a graceful transition to lower levels
- Visual connection between the exterior and interior
- Barrier-free entrances that are part of the main entry sequence and not a separate path.

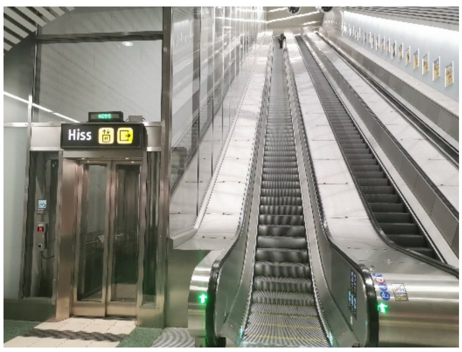

Figure 12. Escalators and inclined elevator in Stockholm (photo: R. Ting)

These issues/approaches/caveats can all be identified as significant among various case studies.

The book then goes on to suggest several design patterns that can mitigate underground building problems and increase user comfort and these also can be found in the case studies. The experience with sunken courtyards is one that deserves a special mention.

Figure 13. High quality access - Loading dock within the Meritex Lenexa mined space (photo: R. Sterling)

Sunken courtyards can be beneficial both for transitions to underground spaces and also for the provision of natural lighting to underground levels. However, they may present some operational issues related to flooding in heavy rains, snow removal in winter climates, etc. Open air structures above entry points can provide some protection and identification of the entrance point but do interfere with ground-level vistas.

Some selected other observations from the case studies that do not neatly fit into the design issues or patterns discussed above relate to:

- Need for staff control over entry area and its implications for entry design
- Available access too small or not practical for construction or planned use
- Impact of large entrances on air flow and ventilation within the facility
- Arrangement of access points to support existing commercial area and street life
- Increasing requirements for access to deep underground spaces
- Effective restriction of heavy vehicle access above an earth-covered building vs design requirements.

5.2 Layout and spatial configuration

Choosing the depth and shape of an underground facility is an important step in the design process but may be strongly controlled by the site size and configuration or the local geological conditions. Design objectives proposed in Carmody and Sterling were:

- Interior layout that is easy to understand with a distinct interior image
- Stimulating and varied interior environment for occupants and visitors
- Visual connections between the interior and exterior environments
- Feeling of spaciousness with extended interior views and/or manipulating room size and shape
- Protect privacy as much as possible.

Figure 14. Children-themed wall decoration, Taipei City Mall (photo: R. Sterling)

Specific design patterns were suggested as beneficial to be considered. From the case studies, these design objectives and design patterns can all be seen to have been implemented to good effect in various examples.

Some specific observations from the case studies can also be mentioned in this regard:

- The interplay between interior views and loss of privacy could be seen by the covering of interior windows separating private spaces and public areas

- As the complexity of underground networks has increased, better attention on system-wide wayfinding systems are needed
- Poor connectivity in portions of underground networks can lead to underperforming areas in terms of commerce with less vitality as well as potential security issues during low-use hours
- Overcrowded underground areas can become oppressive to the users – particularly when wayfinding is difficult (e.g. the “Pinball” area of Les Halles)
- A facility such as the Meritex Lenexa Executive Park provides a high degree of adaptability because individual uses are subdivided within a regular room-and-pillar cavern layout
- A number of technical (e.g. waterproofing) and life-cycle issues point towards the desirability of keeping underground facilities with simple external shapes and flexible interior volumes
- The main determinant of adaptability to a different future use for rock structures is the size of a tunnel or the span and height of a cavern
- The portals to underground cavern systems need careful planning to allow facility extension
- The design of the operational access points for underground buildings, tunnels or caverns should consider the future need to replace major items of equipment and logistic movement.

5.3 Interior elements and systems

The design objectives proposed in Carmody and Sterling were:

- Stimulating indoor environment but not oppressive
- Connections with the natural world plus effective signage to facilitate orientation
- Feeling of spaciousness and warmth with high-quality finishes and furnishings
- Fresh air and thermal comfort.

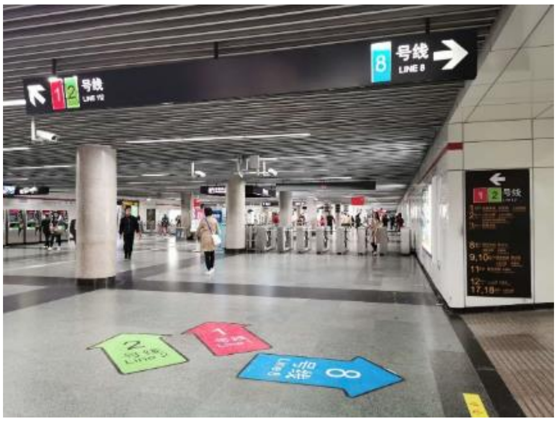

Figure 15. Ceiling and floor signage in People’s Square underground network in Shanghai (Courtesy of Shanghai People’s Square, Dimei Mall and Nanjing Univ.)

The experience from the case studies generally supports these design objectives but does show that the users do not always appreciate the design aesthetic created by the building architect – especially when other problems with the building or work setting are present.

The design patterns proposed in Carmody and Sterling that would respond to those objectives were:

- Colorful, warm and spacious environment with uncluttered furnishings
- Well ventilated and comfortable environment with clear wayfinding
- Pattern, line and texture and natural elements and materials
- Sculptures, manmade artifacts, paintings and photographs
- Mirrors for feelings of spaciousness and to reflect light
- Alcoves and recesses plus transmitted and reflected exterior views.

Again, the usefulness of these design patterns is generally supported by the experience of the case studies. However, it is worth noting that the use of transmitted and reflected views was not as effective as envisaged due to problems with maintenance or the limited area from which the view could be seen.

An issue that did not appear in the objectives or patterns noted in Carmody and Sterling but affected user comfort in several of the underground case studies was the issue of occupation of areas within the underground spaces by the homeless. Secluded spaces that were accessible to the public were often an attraction for the homeless.

Figure 16. Main arena at the Osaka Municipal Central Gymnasium (photo: R. Sterling)

5.4 Lighting

Providing for natural lighting where possible and designing artificial lighting to provide an effective, interesting and welcoming interior environment are important elements in the design of underground facilities. The design objectives for lighting proposed in Carmody and Sterling were:

- Well lit spaces using natural light where possible
- Artificial lighting to simulate the characteristics of natural light
- Lighting to enhance feelings of spaciousness and create stimulating and varied environments.

The proposed design patterns that would respond to the above objectives were:

- Natural light through windows and skylights
- Transmitted and reflected natural light or artificial light with natural characteristics
- Skylights and wall panels with artificial backlighting and indirect lighting of ceilings and walls
- Dark and ambiguous boundaries and patterns of light and shadow.

Figure 17. Angled glazing providing light and view to the -2 level at Williamson Hall (photo: R. Sterling)

Examples of attention to these objectives and use of the design patterns could be identified across the case studies – particularly for those where human comfort in the space was important. Some issues with lighting will be mentioned in connection with maintenance.

5.5 Life safety

Life safety for underground facilities involves both architectural aspects and technical systems. Such components include:

- Clear internal organization and egress with compartmentalization and places of safe refuge
- Safe vertical egress with clear signs and emergency lighting
- Effective detection, alarm and communication systems

- Effective smoke removal and air handling and effective fire suppression
- Fire resistant construction and restriction of hazardous materials.

Issues of interest observed in the case studies are:

- In the National Library of Sweden archives, only a small spiral staircase is available for emergency egress and the depth for exiting can be as much as 40m. Staff using the underground archives must be fit enough to be able to climb the stairs.
- The Meritex mined space uses its driveway area as a surrogate outside space. Occupants can walk or drive horizontally to the outside of the mine. Takayama uses horizontal smoke-protected exit passageways to meet the maximum exit distances from all parts of the cavern.
- In Les Halles and La Défense, the provision of fire fighting truck access to a belowground level allowed that level to be used as the reference ground level for fire safety purposes.
- The fire safety approach for the Gjøvik arena was to remove smoke from the top of the arena cavern while providing a safe zone in the concourse area around the arena. With novel underground projects within an existing regulatory environment, special efforts and time may be needed to gain approval for the project.

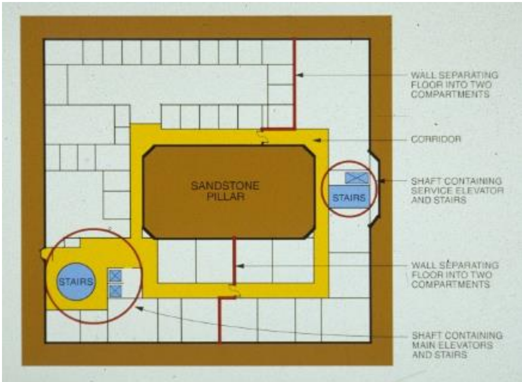

Figure 18. Compartmentalization of mined space in the Civil Engineering Building (drawing: J. Carmody)

- In Montréal, a key aspect of providing a safe environment is the effective collaboration among the many private and public entities that control different aspects and individual spaces within the overall system – endorsed from the executive level in each organization.
- Significant but not catastrophic fires had been experienced in two of the case study facilities – the unsprinklered ArtEZ facility and the P-City Forum parking.

6. Technical Design

This section summarizes the aspects of technical design that have a strong relationship to the usability and acceptance of underground facilities as well as to their comparison with aboveground facilities. Following this logic, four key technical aspects of underground facility design are given particular attention below: geotechnical design, waterproofing/drainage, air quality and energy.

6.1 Geotechnical design

Only a few particular issues that were discussed as part of the case study reviews are identified below:

- **Shotcrete versus bare rock in caverns.** In Scandinavia, shotcrete is generally used as a support or covering layer in occupied rock caverns. If bare rock is exposed, it is generally in the walls of a cavern. Even if shotcrete is not required for overall cavern stability, the shotcrete (typically coupled with a reinforcing mesh and rock bolts) prevents the potential of ongoing dropout of rock pieces from the cavern roof.

- **Longevity of support elements.** Since underground structures are expected to last a very long time, it is important to consider the longevity of the key support elements for an underground structure and how such support elements might be replaced in case of significant deterioration. The more inaccessible but critical components of the structural systems for underground facilities include: rock bolts, tie backs, tie-down piles, etc.
- **Maintenance and accessibility of records for underground facilities.** The geotechnical conditions and existing structural provisions for an underground facility can be more difficult to be determined than in the case of a typical aboveground building. This puts a heavier responsibility on those managing an underground facility to maintain good records about the geotechnical conditions and structural design for the facility and to ensure that these records would remain accessible over time.

6.2 Waterproofing and drainage

Perhaps the most important factor in the future "success" of an underground facility is whether the facility remains sufficiently dry and unaffected by water leakage. Getting it done right the first time is critical because water leakage problems may be difficult or impossible to solve "after the fact".

While a number of case study facilities did not report leakage as a significant issue, for others it was a major ongoing problem that threatened the future usefulness of the structure. Some unusual approaches used successfully in the case studies included: use of a welded stainless steel waterproofing layer on the domes of the Osaka Gymnasium and the use of a box-within-a-box approach for the ArtEZ facility. A few facilities had been able to solve initial water leakage problems by waterproofing repair or the installation of internal drains to capture the leakage. In some cases, continuing leakage contributed to high humidity and the development of molds and fungi within the facilities with noticeable musty smells. When this occurs, it can have a very detrimental effect on a user's perception of the building.

It was also noted that:

- Complicated building envelopes were often associated with leakage issues
- Subsequent building modifications may introduce leakage problems
- For a few facilities, building aging appeared to be related to increasing leakage issues
- Skylights and angled glazing may present leakage issues
- Minor leakage can be mainly an aesthetic issue for internal cavern finishes but may also have a disproportionate effect on interior elements
- Leakage was turned into a building feature in two facilities: Kungsträdgården station in the Stockholm metro and Temppeliaukio church in Helsinki
- Corrosion protection is very important for suspended water protection layers that are poorly accessible after construction
- Monitoring and ensuring adequacy of drains, sumps and pumps are important
- Drainage plugging can occur and provisions for cleaning drains may be needed
- Regional groundwater level changes may affect drainage and waterproofing systems.

Figure 19. Drip pans in the Helsinki pedestrian tunnel system (photo: R. Ting)

6.3 Air quality aspects

Poor indoor air quality is often a strong contributing factor to negative impressions of an underground facility. Included under this heading are the physiological implications of poor air quality due to issues such as high humidity, mold and fungal growth, radon, carbon monoxide, carbon dioxide, etc. as well as the perceived unpleasantness of the interior space due to a damp, musty, smelly or stuffy environment.

The following general issues have been noted from the case studies:

- Having only limited areas aboveground for service functions can cause air quality problems, e.g. an air intake placed near to a loading dock
- Differences in sensible and latent cooling loads for underground buildings can cause temperature/humidity control issues without careful design or the use of reheat systems
- Leakage areas can support mold and fungal growth leading to poor indoor air quality.

6.4 Energy aspects

Underground facilities derive their energy conservation benefits primarily from the more stable ground temperatures compared to exterior cold weather conditions in winter and hot weather conditions in summer. To achieve good energy performance, however, it is necessary that the shallow buried and exposed portions of the facility structure are properly insulated and that unwanted/un-needed ventilation be controlled. The relative energy performance for the different types of underground facilities will also vary with required ventilation capacity and rates and the need for precise control of the interior environment.

In the following discussions, various energy performance issues that can be noted from the case studies are reviewed:

- The case study data collection included 11 rock cavern structures in the Scandinavian climate (cold winters and relatively mild summers). There were generally considered to be significant energy advantages to putting most types of facilities underground in this climate.
- For rock cavern structures elsewhere, the natural cavern temperatures are for the most part used as the operating temperature for the underground facilities and, if specific uses, require a higher or more controlled temperature, the temperature difference is not large. This gives most of the facilities a very favorable energy comparison with most of the energy use going to lighting and ventilation.
- The P-City Forum facility pointed up the importance of controlling unwanted airflow in winter. When speed doors were retrofitted at the entrances, energy use in the facility dropped by a reported 91%.
- Five cut-and-cover buildings reported good energy performance (Pusey, Taipei, Williamson, Mutual, Caer Llan) with two facilities providing detailed energy data. The Caer Llan dormitory was able to operate for several years as essentially a zero energy use building in terms of heating and cooling because it had 1-2m (3.3-6.6ft) of soil on the roof plus insulation and passive solar gain through its southerly facing windows.
- A further seven cut-and-cover buildings (Walker, Osaka, Azalea, Nagoya, Civil Eng., EDD Annex, Wildwood) were felt to have generally favorable energy profiles but noted some specific attributes that impacted their energy performance.
- Three facilities had energy conservation systems (active and passive solar) that were abandoned due to high maintenance requirements. (Civil Eng., Williamson, EDD Annex).

- No specific information on embodied energy for the various facilities was collected in this study.

Although little specific energy consumption data was collected, the performance of the underground facility case studies appears to have been in line with expectations and analyses. The energy conservation benefits from placing a facility underground are generally good but are strongly impacted by the type of use, ventilation and temperature/humidity control requirements.

7. Operations and Maintenance

The case study experiences vary widely in terms of whether one can say that maintenance is easier underground or easier for an aboveground building or whether there is little difference. A big determinant of the answer is whether the facility waterproofing / drainage combination has been successfully accomplished.

- At least seven of the case studies have had serious water leakage issues and, in one case, Walker Library, this contributed to its abandonment and redesign as an aboveground facility.
- Both the underground swimming pools in Norway (Gjøvik, Holmlia) were being renovated at the time of the facility visits in 2019. There had been significant corrosion and deterioration but the required renovations were occurring much later in the pool's life cycle than for aboveground pools (40 years versus 25 years).
- The long hours of operation and critical nature of many underground infrastructure elements limit the availability for inspection and repair/rehabilitation work and makes such underground facilities difficult to maintain.
- The presence of water leakage affects many aspects of maintenance including damage to interior building finishes and corrosion of equipment and fittings within the facility.
- Poor attention to clearing courtyard drains of leaves or other blockages can lead to building flooding during subsequent heavy rains (e.g. Civil Eng. and Williamson).
- In addition to the flooding issue, exterior sunken courtyards used as entrances in a winter climate typically have exposed steps that require additional maintenance to keep them snow and ice free along with the accompanying disabled access ramps.
- Where novel technologies or non-standard building arrangements – including landscaping elements, lighting and view systems and solar collectors – are used, this must be combined with a plan for their maintenance and an understanding of who will have the necessary know-how and interest to maintain the systems in the long-term.

Figure 20. Planters and Engelman Ivy in Williamson Hall courtyard (photo: BRW Architects)

8. User Acceptance and Health

A key question for a building owner, developer or designer planning an underground facility is how acceptable the environment of the facility will be to the people who visit the facility and, typically more critically, to those who will work in the facility. This section concentrates on the overall outcomes for the people themselves and relays some of the experiences and opinions of the various case study responders relative to these questions.

All the case study responders were asked about the level of acceptance of the underground facility and any special offsetting benefits that may be provided for people working in the facility. A few facilities had significant issues but most facilities reported either no problems or some minor issues.

Since the case study responders are not experts in studies of social settings, psychology or physiology, this is not a scientific assessment. Rather, it is a useful set of experiences that help to point out the extent to which underground facilities may suffer from issues of dissatisfaction or health-related concerns and what aspects of underground facility design are most responsible for such experiences and issues.

For a recent science-based study of the psychological and physiological issues relative to underground space use, the reader is referred to the 5-year project carried out by Nanyang Technological University as part of the Singapore Land and Liveability National Innovation Challenge. This study has produced many research papers that have valuable information regarding the assessment and design of underground working environments including extensive referencing to prior work in these fields. References on psychological and social factors include Lee et al (2016, 2019), Soh et al (2016), Tan et al (2018) and references covering physiological effects include Nang et al (2019) and Roberts et al (2016).

A few examples noted from the case studies are highlighted below:

- A person's view of their work environment is partly a direct assessment of the quality of the space and the physical work environment but it also reflects their expectations for what the work environment for their job function should be like and what comparisons to prior work settings or to co-workers' settings are being made.
- Not everyone reacts in the same way to the idea of being underground or to specific interior environments.
- Radon measurements were reported by a few case studies but none were reported to be at problem levels for the usage of the space.
- Temperature and humidity control can affect the experience of being underground even when not reaching to the level of a health issue.

9. Life Cycle, Resiliency and Sustainability

The fact that the median age of the facilities included in the case studies (37-38 years) is approaching a typical target lifespan of 50 years, and is well above the typical economic analysis life span for a commercial building of say 20-25 years, allows some insight to be derived as to how these underground facilities are faring in terms of longevity, life cycle performance, resiliency and sustainability.

For all but one of the 42 case studies, the facilities in question were still in operation and serving a useful function for a company, institution or for society. The one facility (Walker Library) that was closed after 31 years of service, had problems both in terms of its assessments of suitability for its intended purpose and in terms of its technical details – with the latter certainly affecting its overall assessment by the owner. On the other hand, a campus library (Pusey Library) was still lauded as the right design choice and a pleasing building after 44 years of service.

Assuming that an underground facility is designed to fulfill its intended function at the outset, its life-cycle performance becomes significantly dependent on three issues:

- Does the technical performance of the facility continue to provide a quality environment for the users and a long life for the structural components and finishes in the facility?
- Does the original function or mix of functions remain valid?
- If the facility needs change, can the building be adapted to serve the modified needs or be repurposed to continue in a new capacity?

From the case study observations, the longevity is generally very good, especially when water leakage issues are minimal. However, future adaptability to new uses or circumstances needs more thought.

9.1 Maintenance / Adaptability / Reuse / End of life

As a building or facility ages, various problems may need attention. Some of those may be present due to design or construction defects and some may appear due to aging or corrosion of materials, wear of machinery, structural movement, poor environmental conditions, etc. This happens in any type of building and, hence, the need is to identify those issues that need special attention for underground facility design. For example, the waterproofing on an underground building is shielded from many environmental effects (e.g. temperature, UV exposure, etc.) and should ostensibly have a very long life. The difference is that when a waterproofing issue occurs with an underground building, the consequences and cost to repair are typically much more severe than for an aboveground building and it may prove difficult to achieve an acceptable result through a repair activity.

Based on the case studies, some issues involving maintenance, adaptability, reuse and end-of-life for underground facilities are highlighted:

- Inclusion of novel landscaping, special energy, lighting or mechanical systems can create ongoing maintenance issues
- Provisions for maintenance of drainage elements can be important
- Minor leakage can create disproportionate effects on deterioration of equipment and fittings
- Access for maintenance and replacing major equipment items must be thought through
- Poorly used or unused spaces still need good maintenance and control
- Adaptation or expansion of a network or facility needs better consideration in initial design
- Major upgradings of large transportation complexes are particularly challenging
- At the end of life, if not planned for reuse, should the excavation, cavern or tunnel be backfilled to prevent long-term maintenance problems or potential collapse? If not backfilled, who will provide ongoing inspection and maintenance? Who will maintain the records of the facility that was there as well as records of what ground modifications and structures remain?

Figure 21. Partial-height flood door at entrance to Taipei Metro (photo: R. Sterling)

9.2 Resiliency

With the increased interest in resilience of urban areas and local and national infrastructure, this study included questions about the resilience of the case study facilities with respect to various types of impacts. It can be inferred from the experience of some of the case studies that owners are having to adjust their protections (particularly against flooding) due to the impact of climate change on storm intensities and (for coastal facilities) against sea level rise. Further discussion of resiliency and underground space use can be found in Makana et al (2016) and Nelson and Sterling (2012).

9.3 Sustainability

Underground facilities generally have positive implications for the environment. Almost all the case studies are judged to have environmental benefits for their community or surroundings in terms of land use and aesthetics. Some detrimental aspects are the potential impacts on groundwater and other underground resources which should be considered and evaluated during planning and design. Likewise, the energy use implications of the case studies are mostly positive with some caveats with regard to such issues as embodied energy and the need for HVAC design that reflects the particulars of both the above and below ground climate.

Given the age and the variety of types of facilities and locations for the case studies, it is difficult to draw hard conclusions regarding the economy aspects of sustainability based on the information collected. However, it is clear in many cases that cost was not the major criteria in making the choice for an underground facility. The attributes of an underground solution (providing the needed facility in the right place, saving land costs, providing a pedestrian friendly environment, using particular attributes of underground facilities, etc.) were more critical. Another aspect of economy in terms of underground facilities is the extent to which an underground facility enables a healthy economy which otherwise may not have grown to the same extent.

The societal aspects of sustainability imply the need to create a well functioning society which can remain stable over long periods of time. The aspects of life involving culture, history, recreation and the arts are important to the humanity that promotes such stability and sustainability. In high density, compact cities, underground facilities can fill a critical role that could not be met in other ways – easing the functioning of urban societies. Further discussion of these issues can be found in Bobylev (2009) and Sterling et al (2012).

10. Conclusions

The actual performance of a variety of underground facilities over decades of use provides an important set of testimonials that underground facilities can perform well and be well-liked facilities but that great care is needed around key design decisions and specific technical parameters to avoid problems that can be difficult or impossible to address later. As for most facility types, change of use or ownership is possible over the long-term. Future adaptability of an underground structure is something that needs more attention during initial design.

For the human factor design issues, most of the postulated design issues and suggested design patterns can be found among the case studies and are still considered to provide good guidance for successful design practices. However, the case study experiences do provide a variety of caveats for some design approaches.

In the technical area, waterproofing and drainage emerge as key issues that may affect the operational success as well as the perceived success of an underground facility. The presence of serious leakage issues or less serious but nagging issues in many of the case studies suggests that a greater emphasis needs to be placed on this issue in the design and specification of underground projects. Once the facility is built, leakage problems are hard to find and fix. Issues of poor air quality likewise tend to reinforce negative expectations regarding underground spaces. With proper care in HVAC design and when significant leakage issues are avoided, good air quality is not difficult to provide in an underground structure.

Maintenance of underground facilities provides some mixed assessments. Natural underground openings often exist over geologic time spans and the absence of UV light, major temperature variations, windstorms, etc. provides an environment in which many types of materials are slow to degrade and will provide a long life. However, modern underground structures do use materials that can degrade or corrode in an underground environment and, for many public use types of underground structures (e.g. metro stations, road and rail tunnels, pedestrian networks, etc.), the access for inspection and repair in terms of time and physical accessibility can be difficult. Several of the case studies had issues with difficulty in replacing or repairing major equipment items that had been installed during construction. The leakage mentioned above also is a major maintenance issue and even small amounts of leakage in the wrong places can cause damage out of proportion to the scale of the leak.

Only a few of the case studies indicated that there were issues in terms of user acceptance and/or health concerns for the facilities in question. For the facilities that had problems, there were often also air quality, temperature or other physical aspects of the particular facility that were contributing to the acceptance issues.

The safety and resilience of underground facilities can be a major asset, however, the changing climate, rainfall intensities, sea level rise, etc. are putting more emphasis on the rapid flood protection of entrances to underground systems and other critical surface connections such as ventilation shafts.

Most of the projects in these case studies have fared well over decades of use and have validated the decision to build the facility underground. Nevertheless, there are plenty of lessons to be learned from both the successful projects and the not-so-successful projects. The research team hopes that planners, designers and decision makers involved with underground structures will be left with the overall sense that a well-designed underground facility, built underground for the right reasons and with the capability for future adaptation can be a long-term asset to an institution or to society.

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