Advances and Challenges in Underground Space Use in Singapore

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ABSTRACT: Despite its promise and many benefits for sustainable urban development, the use of underground space has tended to be the last resort, due to high development cost and the complexities in the planning and development of underground space. In 2010, the Economic Strategies Committee of the Singapore government made developing underground space part of the government's long-term economic strategy with specific recommendations on master planning, geological investigations, investment in research and development, and various policy issues. With this, the use of underground space has been elevated to a strategic level and has become an economic imperative in land-scarce Singapore. The ESC report also recommended that the government should take the lead in catalyzing the use of underground space. Based on these recommendations, the Singapore government has taken various initiatives and studies, and initiated various research projects in support of these initiatives. This top-down strategy has also made it possible to plan and coordinate the development of underground space in a holistic manner, and helps overcome the key challenges of the systems. This paper gives a review of advances in underground space development, highlights some key challenges, and discusses the various recent studies and planning issues, and examines possible strategies for future use of underground space in Singapore.

KEYWORDS: Underground space, Rock caverns, Singapore

1. INTRODUCTION

With a high population density and continually developing economy, Singapore faces a severe lack of land space for sustainable development. The increasing population, coupled with the government plan for more green space for the population, means more competition for land.

Traditionally, Singapore has tackled the land constraints with high-rise buildings and land reclamation. From her independence in 1965 to 2014, Singapore's land size grew by 22% by land reclamation (The Economist, 2015). However, land reclamation is reaching its limits and faces increasing challenges due to geographical boundaries, increasing water depths, increasing cost of sand supply, environmental concerns, and geopolitical issues. For high-rise buildings, Singapore also has to deal with additional constraints due to civil aviation and defense needs primarily due to the small size of the country, problems most other urban areas do not have.

Thus, underground space development has become an economic imperative in land-scarce Singapore. In October 2007, the government, under the Ministry of National Development, set up an inter-agency Underground Master Planning Task Force that aims to map out the long-term development of the underground space, bringing the underground space development to a strategic level. In 2010, the Economic Strategies Committee made developing underground space an important part of the government's long-term economic strategy.

2. THE LAND SQUEEZE

Table 1 shows the change of land use distribution in Singapore from 1960 to 2007 (Malone-Lee 2011).

Land has always been recognized as a constraint by the Singapore government. According to the Department of Statics of the Singapore government, the population in 2013 was 5.5 million. With a total land area of 716.1 km^2, the population density stood at 7,540 persons/km^2. This compares to a population density of 42,852 persons/km^2 in Manila and 21,498 in Paris (Wikipedia, 2015a). In fact, the population density of Singapore is not even in the top 50 cities in the world. However, what makes it unique and more challenging for Singapore is that Singapore is also a country with no hinterland. Singapore would rank 2nd in terms of population density per country after Morocco. Singapore must address both the needs of a modern metropolis as well as the need of a country. The development of the underground ammunition facility by the Ministry of Defence was case in point. No cities in the world have to store ammunitions in their urban area. In fact, most cities do not have to cater for defense requirements in such large proportions as Singapore. The storage of ammunition near the population not only places severe constraints on land use, it also places great demand on safety. This is why underground ammunition storage in Singapore has so much advantage compared to other countries.

Table 1 Land use distribution in Singapore 1960-2000 (Malone-Lee 2011)

Year	Land Area, km^2	Build-Up, km^2	Agri-culture, km^2	Forest, km^2	Marsh & Tidal Waste, km^2	Others* km^2
1960	581.4	162.3	141.7	37.8	45.9	193.8
1965	581.4	177.4	131.6	35.0	35.0	202.5
1970	586.4	189.9	134.0	32.4	32.4	197.7
1975	596.8	228.4	105.9	32.4	32.4	197.7
1980	617.8	275.1	80.9	30.0	26.0	205.8
1985	620.2	298.8	47.1	28.6	18.5	227.5
1990	639.1	311.6	10.8	28.6	15.7	266.4
1995	647.5	319.3	9.3	28.6	15.7	274.6
2000	682.7	324.0	9.3	28.6	15.7	274.6
2012 Est	714.3	418.4	9.3	28.6	15.7	238.2

***Others (water, open space, gardens, cemeteries)**

The land squeeze is expected to get worse according to planning numbers published by the government (Tables 2 and 3). According to the land use plan of the government published in 2013, the expected land use will be 766 km^2 by 2030 when the population is expected to increase to between 6.5 and 6.9 million from the current 5.5 million (National Population and Talent Division, 2013), a net increase of land requirement of about 50 km^2 from 716 km^2 in 2013. Even if the 50 km^2 in land space can be achieved, this only represents a 7% increase, compared to the population increase of between 18% and 25% based on the above numbers (Table 3).

From Table 2, it can be seen that the largest land users are Defense (19%), Housing (17%), Industry and Commerce (17%), and land transport infrastructure (13%), accounting for 66% of the total land. After this group, parks and nature reserve take up 9%, a reflection of the country's drive to keep her reputation as a garden city. It is also significant to note that the amount of reserve land has been reduced from 14% in 2010 to 4% in 2030, leaving relatively little reserve for further allocation after 2030.

Table 2 Land Use Plan for 2010 and 2030 (URA, 2013)

Land Use	Planned Land Supply	
	2010	2030
Housing	10,000 (14%)	13,000 (17%)
Industry and commerce	9,700 (13%)	12,800 (17%)
Parks and nature reserves	5,700 (8%)	7,250 (9%)
Community, institution and recreation facilities	5,400 (8%)	5,500 (7%)
Utilities (e.g. power, water treatment plants)	1,850 (3%)	2,600 (3%)
Reservoirs	3,700 (5%)	3,700 (5%)
Land transport infrastructure	8,300 (12%)	9,700 (13%)
Ports and airports	2,200 (3%)	4,400 (6%)
Defence requirements	13,300 (19%)	14,800 (19%)
Others	10,000 (14%)	2,800 (4%)
Total	**71,000 (100%)**	**76,600 (100%)**

Table 3 A Comparison of Population and Land Use (URA, 2013)

Land and Population	Year 2014	Year 2030	Change
Land size	716 km^2	766 km^2	50 km^2 (7%)
Population	5.5 mil	6.5-6.9 mil	1-1.4 mil (18-25%)

3. OVERVIEW OF UNDERGROUND SPACE USE

Table 4 gives a summary of the major underground infrastructure and storage facilities in Singapore.

3.1 Urban Infrastructure

Like many other cities in the world, Singapore's earlier and main use of underground space has been in the forms of transport and basement for shopping and parking. According to the Land Transport Authority (LTA) Master Plan 2013, Singapore's rail network is expected to double from the current 180 km to 360 km by 2030 (Figure 1). This figure is expected to grow further after 2030 (TODAY, 2015). Most of the new lines are expected to be underground. The rail network in Singapore has been expanding by about 6km per year from 2000 to 2015, and will grow by about 12 km per year in the next 15 years.

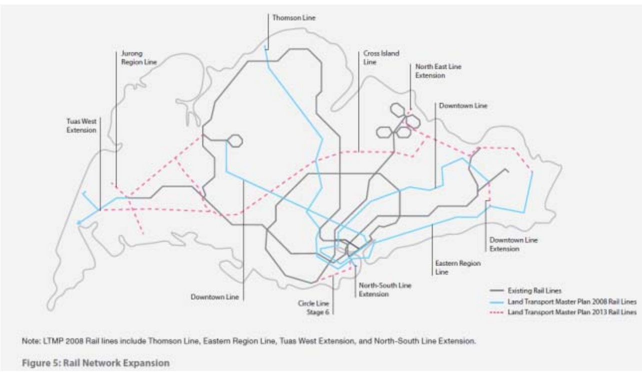

Figure 1 Rail Network Expansion Plan (LTA, 2013)

The Singapore portion of the planned Kuala Lumpur-Singapore high-speed rail is expected to be underground and will further add to the growth of underground rail network in Singapore.

For utilities, the Deep Tunnel Sewage System (DTSS) has an island-wide network of tunnels connected to two major wastewater treatment plants to the east and west (Tan & Weele, 2000; The Straits Times, 2015). The DTSS has won many international awards in the area of water technology, but is equally impressive in terms of its use of underground space. When Phase 2 is completed, the DTSS will have nearly 100 km of main sewage tunnels and deep sea outfall tunnels, 130 km of link sewers, and three underground water reclamation plants (Figure 2).

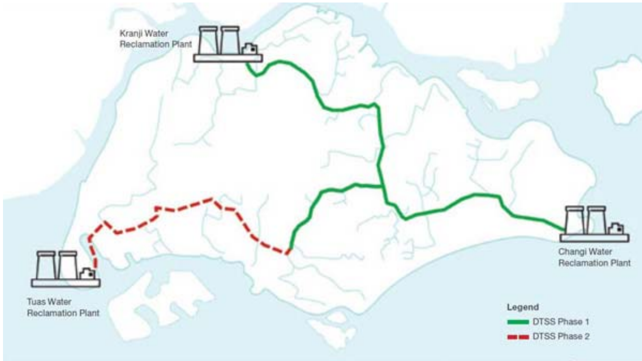

Figure 2 Deep Tunnel Sewage System (DTSS), Singapore's Used Water Superhighway (PUB Website, 2015)

Less known but a well-conceived underground utility facility is the Common Services Tunnel (CST) located under the Marina Bay area. The CST was planned and developed before the extensive aboveground development, with a plug and play concept, and 100% reserve capacity for future development (URA, 2006) (Figure 3). A key success factor in this project is perhaps due to the fact that it was planned and built by the Urban Redevelopment Authority (URA), which was able to take a top down and long-term approach, because of her role in urban planning as a government agency. Some of the key benefits described by URA include minimal traffic disruption, more reliable services, faster laying of services, increased flexibility, a better urban environment, more land for development.

Figure 3 Common Services Tunnel (URA, 2006)

More recently, the on-going Singapore Cable tunnel project is another major effort in placing high power transmission lines in deep tunnels with easy access for maintenance. It consists of two cross island (north-south and east-west) tunnels at 60m below ground. The deep tunnels are designed to overcome the increasing congestion of underground space and utility services in Singapore, especially at shallow depths. They will facilitate faster and more efficient maintenance and replacement of cables, thereby reducing the frequency of road-digging works and thus minimising inconvenience to the public in the long run.

Table 4 Summary of Major Underground Infrastructure Projects in Singapore

Name	**Type**	**Technical Information**	**Commencement and Extension**	**Other Information**	**Reference**
North-South MRT Line	Metro	45km, 27 stations. Partially underground.	First opened on 7 Nov 1987 with 26 stations. A 1-kilometre (one station extension from Marina Bay to Marina South Pier station was opened on 23 November 2014.	Part of the first MRT lines built in Singapore, with most lines elevated.	http://www.lta.gov.sg/
East-West MRT	Metro	57km, 39 Stations. Partially underground.	First opened on 12 Dec 1987 with 49km and 35 stations. Tuas West Extension with four stations, to be completed in 2016.	Part of the first MRT lines built in Singapore, with most lines elevated.	http://www.lta.gov.sg/
Circle Line MRT	Metro	35km, 30 stations. Fully underground.	First opened on 28 May 2009 and fully operational in 2012 (stage 5). Stage 6 includes 4km and 4 stations due to complete in 2015.	First underground depot at Kim Chuan, considered the largest underground depot in the world.	http://www.lta.gov.sg/
North East Line MRT	Metro	20km, 16 stations. Fully underground.	First opened on 20 June 2003. Fully completion by June 2011. A 4km Pungol extension to be completed by 2030.	First line in Singapore to have artwork integrated into all its 16 stations under the Art in Transit programme.	http://www.lta.gov.sg/
Downtown Line MRT	Metro	42km, 33 stations. Fully underground.	Stage 1 opened on 22 Dec 2013. Full line to open by 2016.	Fifth MRT line in Singapore.	http://www.lta.gov.sg/
Thomson Line MRT	Metro	43km, 31 stations. Fully underground.	Underground construction. Expected to open in 2018.	Sixth MRT line in Singapore. First line to encounter significant rock excavation	http://www.lta.gov.sg/
Cross island Line MRT	Metro	Approximately 50km.	Under planning. Expected completion in 2030.	A section is planned to run under the Central Nature Reserve.	LTA, 2013
Jurong Regional Line MRT	Metro	Approximately 20km.	Under planning. Expected completion in 2025.		LTA, 2013
CTE Tunnel	Road	Chin Swee Tunnel: 1.6 km. Kampong Java Tunnel: 0.7km.	Opened in 1991.	The Central Expressway (CTE) tunnels were the only road tunnels at the time. They run under the Singapore River.	http://www.lta.gov.sg/
KPE Tunnel	Road	9 km.	26 October 2007.	Kallang–Paya Lebar Expressway tunnel is mostly cut-and-cover construction.	http://www.lta.gov.sg/

MCE Tunnel	Road	3.6 km tunnel with five lanes in each direction.	29 December 2013.	MCE tunnel comprises a 420-metre immersed tunnel that crosses under the Marina Bay Channel seabed. The deepest point is about 20m below seabed.	http://www.lta.gov.sg/
DTSS Ph1	Utility	A 48km long deep tunnel running from Kranji to Changi, a water reclamation plant at Changi, two 5km long deep sea outfall pipes and 60km of link sewers.	Ph1 completed in 2008 at a cost of SGD$3.4 Billion.	The heart of DTSS Ph1 is the Changi Water Reclamation Plant capable of treating 800,000 m^3 of used water a day. The treated water is then discharged into the sea through deep sea outfall pipes or channelled to the Changi NEWater factory where it is purified into reclaimed water.	http://www.pub.gov.sg/dtss
DTSS Ph2	Utility	A 30km long South Tunnel, 70km of link sewers to cover the western part of Singapore, and a water reclamation plant at Tuas and under-sea outfall. All expected to be underground.	Under planning. Expected completion in 2030.	The water reclamation plant at Tuas is expected to include improved energy efficiency. It will similarly have Newater factory integrated into the water treatment plant.	http://www.pub.gov.sg/dtss
Common Services Tunnel	Utility	The complete system has 20km of tunnels at 2.4m below ground. Main tunnel and branch tunnels have height x width of 14mx5m and 8.7mx4.8m.	First phase completed in 2006.	Houses various utility services, including district cooling, for the 320ha Marina Bay area. It has 100%.	http://www.ura.gov.sg/skyline/skyline06/
Cable Tunnel	Utility	35km, 6.5m diameter, 60m below ground,18 station buildings with shaft access.	Under construction. Expected completion in 2018.	For electricity cables. Consists of one N-S tunnel of 18.5 km and one E-W tunnel of 16.5km.	http://www.singaporepower.com.sg
UAF	Storage	Underground ammunition facility (UAF) for the Ministry of Defence built in granite rock.	March 2008.	The UAF was considered a major pioneering rock cavern project in Singapore and achieved direct land savings of more than 300 ha by freeing up the Seletar East Ammo Depot.	The Straits Times (2008)
JRC	Storage	Jurong Rock Cavern (JRC) for storage of hydrocarbon products. About 130 meter below sea bed.	Sept 2014.	Total storage capacity of 1.47mil m^3 under Phase 1. Phase 2 is under planning.	The Straits Times (2014)

Due to the geology of Singapore, most of these underground infrastructure projects have been constructed in soft grounds, although more and more such projects are being constructed deeper in bedrocks or in mixed grounds, including the DTSS, Singapore Cable Tunnel (Figure 4) and the recent the Thomson MRT line.

Figure 4 Route alignment of the Singapore Cable Tunnels (Singapore Power, 2012)

3.2 Rock Cavern Development

Table 5 summarises the major activities related to rock cavern development in Singapore.

The study of underground space in rock cavern started in the 1980s (Broms, 1989). A series of feasibility studies completed in the 1990s covered different geological formations in Singapore (e.g., Broms and Zhao 1993, Zhao et al 1994, Zhao and Lee 1996). The set-up of the Underground Technology and Rock Engineering (UTRE) program in Nanyang Technological University (NTU) marked a concerted national effort for research and development in rock engineering and cavern development.

During this period, the underground technology and rock engineering research team at NTU performed several large-scale feasibility studies, including geological explorations for cavern development, covering much of the Bukit Timah granite area and some selected Jurong Formation area. They also studied some specific cavern development projects, notably the Underground Science City (USC) (Zhao et al 2001), caverns for warehouse (Wallace et al 1995), the library at NTU (Zhao and Bergh-Christensen 1996), fresh water storage (Bye et al 2004), the Science Centre below the Mount Faber, and many others.

The major breakthrough in cavern development in Singapore was the construction of the Underground Ammunition Facility (UAF) in rock caverns in the Bukit Timah granite (Figure 5). Construction of the UAF, led by the Defence Science and Technology Agency (DSTA), began in 1999 and was commissioned by the Ministry of Defence in 2008 (The Straits Times 1999, 2008). The relocation of the ammunition storage from surface to deep rock caverns released about 4 km^2 surface land in Seletar East, which is being developed into a thriving Aerospace Hub. The UAF demonstrated the viability and significant benefits of using rock caverns to create space and improve safety, and served as a catalyst and case study for many later studies and thinking on the use of rock cavern space (e.g., Zhao et al 1999a, 1999b, 2000, 2001, 2004; Bye 2004).

The success of the UAF also gave a major boost to the second major rock cavern project, the Jurong Rock cavern project for oil storage (Zhao et al 2004), which was officially commissioned by Singapore's Prime Minister in Sept 2014 (The Straits Times 2012, 2014). The JRC caverns, constructed beneath the seabed at the Banyan Basin in Jurong Island and located about 150m below ground, has a storage capacity of about 1.5 mil m^3 (Figure 6). The JRC achieved land savings of about 60 hectares.

Table 5 Summary of Rock Cavern Development in Singapore

1990-1994:
- Feasibility study of rock cavern construction in the Bukit Timah Granite by PWD/NTU

1995-1998:
- Feasibility study of rock cavern construction in the Jurong Formation by NTU/PWD
- First Tasks Force on promoting use of rock cavern was set up and led by URA, and the Tasks Force recommended MINDEF to take the lead.
- Feasibility study of the UAF (underground ammunition facility) by MINDEF/DSTA
- Establishment of Underground Technology and Rock Engineering (UTRE) program at NTU supported by DSTA

1997-2000:
- Feasibility study of the Underground Science City (USC) by NTU/JTC
- Construction of the UAF started in 1999 by MINDEF/DSTA

2001-2007:
- Feasibility studies of hydrocarbon storage caverns at the Jurong Island (JRC) by JTC and NTU.
- Other preliminary feasibility studies of underground space using rock caverns, e.g., Science Centre below Mount Faber, Jurong Bird Park extension into the Jurong Hill.

2007-2014:
- JRC (Jurong Rock Caverns for hydrocarbon storage) construction started in 2009 and commissioned in 2014
- Government set up inter-agency Underground Master Planning Task Force (UMPTF)
- Further feasibility study on the USC at Kent Ridge commissioned by JTC
- Feasibility study on underground warehouse caverns at Tanjong Kling by JTC
- Feasibility studies of several industrial usages of rock caverns by JTC/MND
- Nanyang Centre of Underground Space (NCUS) established at NTU in 2012
- Underground space master planning study of the NTU campus
- MND research and development call on Sustainable Urban Living and Land and Liveability National Innovation Challenge

Figure 5 Underground Ammunition Facility (UAF) cavern after excavation (The Straits Times 2008)

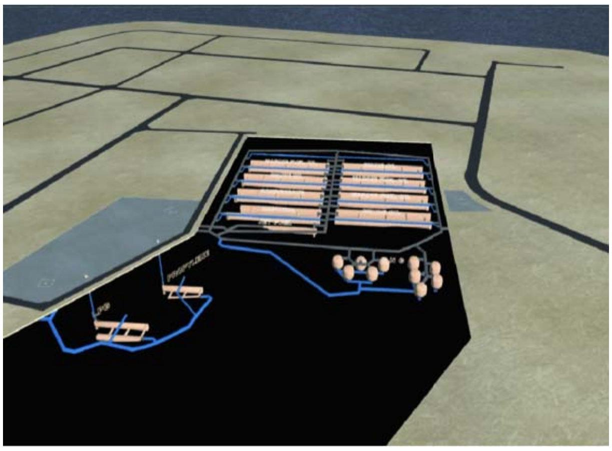

Figure 6 The Jurong Rock Caverns (JRC) under construction (Courtesy of JTC and SINTEF-Tritech-Multiconsult Consortium)

4. RECENT INITIATIVES AND STUDIES

The use of underground space in Singapore has become part of the overall strategy for long-term economic strategy and is structured as part of urban sustainability. The underground is now recognized as a strategic resource whose use must be planned and optimized. This shift in thinking however did not come easily.

4.1 Underground Master Planning

In 2007, the government set up an Underground Master Plan Task Force, with the following terms of references defined as its broad objectives:

a. To develop an underground Master Plan for Singapore by identifying potential types of uses and their corresponding benefits to Government, and determining potential locations for such underground uses. A comprehensive underground Master Plan will form inputs to the next Concept Plan Review.

b. To identify imminent potential projects for underground development, resolve technical issues and apply the revised funding mechanism and supporting policy recommendations from AGD's (Attorney General's Department) committee to facilitate their development.

c. For areas studied by AGD's committee on Integrated Underground Development, to surface policy changes necessary to facilitate underground development to AGD's committee

In 2010, the Economic Strategies Committee (ESC) under the Prime Minister's office made specific recommendations on underground space use, and thus elevated the use of underground space to a strategic level (ESC, 2010). Under "Create land and space", the ESC made a key recommendation to invest in creating and using underground space, and that the government should take a lead in:

a. Creating basement spaces in conjunction with new underground infrastructural developments (e.g. rail) to add to its "land bank";
b. Developing an underground master-plan to ensure that underground and aboveground spaces are synergized and better integrated with surrounding developments and infrastructure;
c. Establishing a national geology office to collate underground information that will benefit both private and public sector efforts in underground development;
d. Developing a subterranean land rights and valuation framework to facilitate underground development; and
e. Investing in underground development R&D and directly investing in cavern level.

The government initially defined three key objectives for the underground master plan:

- To reflect existing and planned underground uses
- To identify and safeguard other possible locations for underground developments (e.g. at cavern and at basement levels)
- To guide agencies in the planning and implementation of new underground developments

Clearly, the importance and need to develop an underground master plan was recognized early in defining the Terms of Reference for the Task Force. However, the difficulties and challenges, especially the type of technical and policy input required, were probably underestimated. One major challenge was the lack of 3D geological information (Tor et al 2005). Other challenges include identifying the types of underground space applications and developing a vertical zoning framework to address the 3D nature of underground space use, coordination and integration among various government agencies, different applications, and integrating aboveground and underground space development (Zhao and Künzli, 2016).

4.2 Planning Studies

To address these important information gaps, the government conducted a series of studies, set up a National Geology Office that is charged with investigating the bedrock geology with the main aim of providing 3D geological data for underground space planning and developing a cavern suitability map, and introduced two research schemes under the Ministry of National Development's Sustainable Urban Living and under the National Research Foundation's (NRF) Land and Livability National Innovation Challenge, known as L2 NIC (NRF, 2013). It is worth noting that the NRF launched only two National Innovation Challenges till then. The first one was on energy. Under the L2 NIC, creation of space was one of four key focus areas.

Many studies have been conducted under the Task Force. These include rock cavern applications for power stations, water reclamation plants, incineration plants, landfills, water reservoirs, warehousing and logistics, data centres, and port and airport logistics (The Business Times 2008; Zhou and Cai 2011). Two significant studies for rock cavern development are the Underground Science City at Kent Ridge (Zhao et al 2000, 2001; The Business Times 2009), and the underground warehousing, logistics facilities & Data Centre Hub at Jurong Hill/Tanjong Kling. Recently, the government has planned to study an underground goods mover system (JTC, 2015) and an underground drainage and reservoir system (The Straits Times, 2015). The underground goods mover system (UGMS) will attempt to link several planned industrial production and distribution centres, some of them could be in underground rock caverns, to the future Tuas Port which is being planned. The underground drainage and reservoir system (UDRS) is envisaged to have a very large underground reservoir in rock caverns connected to various drainage tunnels. It will be a significant attempt to address two sustainable issues of water resources and flood control, and will aim to combine with pumped storage to help regulate the energy supply while providing the necessary water circulation. In addition, underground reservoirs will also have the benefits of enhanced security against sabotage and reduced evaporation. The combined use of the UDRS will be the first of its kind in terms of scale and applications.

Another very important study recently undertaken by the government is a benchmarking study (URA 2013). At the time of writing this paper, results of the study have not been published. Nevertheless, the objectives and scope defined for the study can help explain the importance of this study.

Objective:

- Develop holistic and comprehensive framework to enable more extensive use of underground space by establishing guidelines for underground space planning and development in Singapore.

Scope of Study:

- Quantitative comparison study of underground planning and development – Singapore vs international
- Identification of best practices in policy, legal, standards, and case studies
- Identification of gaps and improvements
- Developing standards and codes of practice
- Format for underground master plan

Expected outcome will include guidelines on:

- How to identify locations for underground use and determine suitable land uses;
- Planning for co-location of multiple uses and sharing of common infrastructure/facilities;
- Ensuring coordination and interaction between above-ground and underground developments;
- How to incorporate flexibility in the planning and design of underground spaces so that they could be adapted for different uses
- Inter-agency coordination to facilitate more extensive use of underground spaces in Singapore;
- Cost-benefit-analysis model that incorporates both quantitative and non-quantitative parameters.

Clearly, the outcome of this study will be significant for the future development of underground space in Singapore and indeed could serve as a good reference for other urban areas in the world.

4.3 Ownership of Underground Space

In Feb 2015, the Singapore Parliament passed significant two legislations aimed at addressing the issue of ownership and acquisition of underground space, the State Lands (Amendment) Act 2015, and the Land Acquisition (Amendment) Act 2015. The State Lands (Amendment) Act 2015 defines ownership of the subterranean space as “land includes only as much of the subterranean space as is reasonably necessary for the use and enjoyment of the land.” It further defines reasonable use as being: a) such depth of subterranean space as stated in the State title for that land; or b) if no such depths is specified, subterranean space to -30m below the Singapore Height Datum.” Here the Singapore Height Datum is legally defined in Boundaries and Survey Map Act (CAP. 25) of Singapore but is essentially the mean sea level.

The Land Acquisition (Amendment) Act 2015 allows the acquisition of a specific stratum of underground space. This provision will facilitate the development of public projects that require a specific stratum of space.

The objective of the legislative amendment is to facilitate future underground development by the State and private landowners. Hence, the reference point to determine ownership of underground space must provide sufficient certainty on ownership boundaries for both government agencies and landowners to plan for the use of the underground space. The reference point should also not be too cumbersome or complex for general public’s understanding, nor result in excessive administrative costs for both agencies and landowners.

However, what is not clear is some of the more technical issues related to the development of underground space such as first rights of use, liability of one ownership to another, offset required for underground stability, movement of fluids underground and responsibility for flooding underground, as well as entrance for the construction and later use of the underground space. Also, it is not clear if a private person can own some underground space without owning the aboveground land. Clearly, further details need to be developed by the relevant government agencies to address such potential issues.

5. CHALLENGES AND POSSIBLE STRATEGIES

In a seminar on underground space held in Singapore in 2012, Singapore was mentioned at once as both a bad example and good example in the use of underground space. The argument about Singapore being a bad example was probably true for most urban areas, where the underground space was considered as last resort when land was running out for urban development. This argument suggests that Singapore would have been in a much better position in land use had it considered the use of underground space when it did not have to but had planned the use of underground space as part of the overall urban development. At the same time, Singapore was considered a good example, in that the city state was taking a top-down planned and coordinated approach to the use of underground space. A key challenge in the planned use of underground space is the coordination and integration across different government agencies and across different development time horizons. Other integration issues include integration between aboveground and underground development, public infrastructure and private development.

5.1 Complexity of Underground Space Development

Underground space development has a number of features that make it a complex system.

- Underground development projects usually are large in size and budget;
- They often have a long lead time from planning to development;
- They usually have a large number and often diverse types of components or sub-systems;
- They are often multi-disciplined and involve a large number of independent variables that interact in interdependent and often unpredictable ways;
- They usually contain increasing connectivity, either by design or otherwise;
- They involve many stakeholders whose interest in and ability to influence the projects may not be clearly understood and may change over time.

In other words, underground development is dynamic in nature, in which the requirements often change with geopolitical events, involving multiple time scales, which often outlives the technology cycle time, and their boundary conditions are often difficult to define, making it difficult if not impossible to define their inter-relationships.

Given such a complex nature of underground space development, it is necessary to take a holistic approach in its planning, with systems engineering and systems thinking to provide a framework to tackle the complexity and to develop optimum solutions. A systems approach will bring a different and more holistic framework for decision making. The systems approach requires decision makers to view the use of underground space as part of a larger system (e.g. urban development, economic strategy), and to examine the project systems from the life cycle point of view, from planning, design and construction, operations and maintenance, to decommissioning. A whole-of-government approach is preferred and indeed necessary. From this perspective, the Singapore government should be applauded for several initiatives, including the setting up of an inter-ministerial Steering Committee on Underground Development (SCUD) and an inter-agency Underground Master Plan Task Force to provide overall guidance, supervision, and coordination of key underground infrastructure development in Singapore. The appointment of a Coordinating Minister for Infrastructure in 2015 is a reflection of the need for coordination at the national level.

5.2 Justifying the Cost

There is a general perception that underground construction is much more expensive compared to aboveground. As such, cost has been a major barrier to more optimum use of underground space. While many tangible and intangible benefits have been discussed regarding underground space use, decisions on development options are often made entirely on the basis of construction costs, although some efforts have been made to introduce the concept of life cycle cost, or Total Cost of Ownership (TCO). In government agencies, the Cost Benefit Analysis (CBA) methods invariably use directly quantifiable cost (e.g. construction cost) and benefits (revenue, value of land savings), and some market methods (e.g Willingness To Pay) to derive monetary values for those so-called intangible costs and benefits (e.g. environmental, social). Often it is impossible to derive the market value of many intangible and yet important parameters.

Clearly, an alternative approach is necessary to help government agencies to make decisions on a systems view, taking into consideration many other intangible benefits, including those with high strategic significant. It is therefore important to develop tools that allow for effective and fair evaluation of the cost and benefits in a quantitative manner. One possibility is the Analytical Hierarchy Process (AHP), which has been used in many applications for more objective and quantitative comparison of various non-numerical parameters. In such CBA models, cost is treated as one of the variables in a system with a clearly defined objective function, success criteria, and boundary conditions.

5.3 Finding the Underground Space

Underground space development requires much more and 3D geological information compared to aboveground development, as the construction activity takes place directly in the geological material. Because of the 3D nature of underground space development, vertical planning of underground infrastructure is critical in order to develop the necessary underground master plan. The lack of 3D information on existing or even unknown underground infrastructure has proven a major challenge in getting the accurate data for planning. In other cases, both the aboveground and underground are already getting congested, making it necessary to develop in very close proximity to existing underground infrastructure and aboveground buildings. To address such challenges, the government has been carrying out island-wide geological investigations to obtain 3D geological data, coordinating efforts in obtaining 3D data on existing underground infrastructure, and developing plans for vertical zoning for future development.

The relatively flat terrain and thickness soil overburden in the Singapore geology makes it a challenge in finding good access for rock cavern construction. Singapore is of moderately low relief (Zhou and Cai, 2011; Zhao et al, 2012; Zhou and Zhao 2016). Most of land areas range 10-30 m in elevations (Figure 7). The area of highest relief is at the Northern Central of Singapore, Bukit Timah area, where the highest hill rises to 163 m above mean sea level. As shown in Figure 7, most of the hilly areas are in the Bukit Timah formation, where most of the abandoned granite quarries are found. Abandoned quarries are considered good locations for access for rock cavern construction (Zhou and Zhao, 1992). Otherwise, deep vertical shafts will be a main form of access for rock cavern facilities.

The tropical climate is conducive to the erosion and weathering process of Singapore rocks. In the Jurong sedimentary formation, the weathering depth extends to a depth of 45 m or more and is generally deeper in the faulted areas and in the mudstone region, whereas the thickness of the weathered zone for the Bukit Timah granitic formation reportedly varies from 10 to 50 m (Zhao et al 1994a, 1994b; Sharma et al., 1999; Zhou, 2001). Residual soils occupy approximately two thirds of the land area of Singapore. The residual soils derived from the Jurong sedimentary and the Bukit Timah granitic formations are found in the western and central regions of Singapore, respectively.

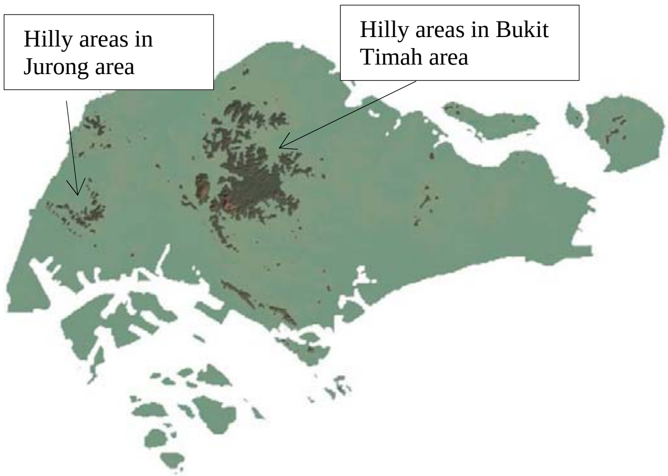

Figure 7 Digital terrain map showing hilly areas (dark color) with elevations higher than 40 m above sea level

5.4 Legal Framework and Policies

Legal and administrative restrictions may act as significant barriers to the use of underground space. The protection of the rights and ownership of existing surface or underground users, the business model, pricing mechanism, the administrative control of national reserves, and the provision of personal safety and environment protection are issues that must be resolved in all cities. In Singapore and many other urban areas, alignment of the underground infrastructure is a major challenge in planning because of land ownership issues. The purchase of surface land or the need to align metro lines to avoid such legal issues can result in less optimum routing or longer tunnels and contribute to the cost of development.

Another interesting issue is whether the government, releasing the potential value of cavern space, should charge a space premium for creating the cavern space. Such a premium would be effectively a penalty. Development controls may also restrict more extensive use of basement space by private developers. In many countries, the excavated rock can be sold to offset the cost of construction as good quality rocks can be used as construction materials such as aggregates. In Singapore, however, if the excavated rocks are disposed of as waste, it is considered a cost in the contract. However, if it is sold, the government charges a royalty and revenue from the sale of the rock goes back to the government, rather than to the project or the agency implementing the project. This situation gives no incentive for the optimized use of the excavated rocks.

5.5 Safety Standards for Underground Facilities

Construction safety is important, and the tunneling community is known for its conservative approach. However, excessive safety requirements artificially increase the cost of construction. After the Nichol Highway Collapse in 2004, the authorities in Singapore introduced more stringent requirements for structural design of both temporary and permanent excavations. No doubt these measures have been intended to improve structural safety. However, these have also made underground construction more expensive and slower, which leaves little room for innovation in design and construction. For rock cavern excavation, setting stringent vibration limits from rock blasting can result in significant increases in rock excavation cost. In the case of Singapore, the majority of buildings are reinforced concrete, which can take substantially higher vibrations compared to traditional masonry buildings in other countries (Zhou et al., 2000). Thus, having rationale vibrations standards will have significant economic benefits for rock excavation. Likewise, meeting fire safety regulations for underground facilities is proving to be major challenge and is high on the research agenda.

5.6 Coordination and Integration

Often the high cost of underground construction is the result of poor planning and coordination, and lack of technical competency in the responsible agency, and lack of integration and coordination amongst different agencies. Thus, coordination among the various government agencies is important for the planning and safeguarding of supporting surface land sites, and integration of aboveground and underground facilities, and different types of underground facilities in matching geological conditions. Dual-use or multi-purpose facilities can help reduce cost of construction but cannot be planned without the full participation of the stakeholders from multiple agencies. The appointment of a Coordinating Minister for Infrastructure signals 'a cultural shift in in the way the civil service tackles challenges that cut across multiple agencies' (Straits Times, 2015), and will definitely help overcome such challenges.

5.7 Managing Public Perceptions and Stakeholders

One major challenge to the planners and decision makers is public perception. While the use of basement space for parking and shopping malls has been accepted by the general public, deep underground rock cavern space still creates some form of unease. Another perception is that underground space is very expensive, perpetuated by some so-called experts who are quick to express their opinions in the media without the necessary studies. This is a challenge that is difficult to overcome if we only look at construction costs and not look at underground space use with a long-term view. A system engineering thinking with the ability to consider the other opportunities is necessary to change or manage this perception. Other public perceptions include dangers in construction and negative environmental impact. In 2013, the Nature Society (Singapore) published a position paper openly opposing the alignment of a section of the Cross Island Line (CRL) that passes under the Central Nature Reserve (CNR), which believed "that the engineering investigations and construction works will severely degrade the pristine habitats within the nature reserve ..." Certainly, the government did the right thing in working with the nature group to conduct an Environmental Impact Assessment (LTA, 2014) and conducting several engagement sessions with the various nature groups. From a systems point of view, the nature group is but only one of the many stakeholders, boundary conditions and limitations which must be considered in the planning and decision making. Developing the CRL under the nature reserve precisely serves the purpose of preserving the nature reserve while allowing the development of transport infrastructure to support the national economic development. Indeed, building a highway or railway above ground on the boundary of the nature reserve, e.g., the existing Pan-Island Expressway and Bukit Timah Expressway, would have brought more impact to the nature reserve than the underground option. For the planners, an early stakeholder analysis would have identified the nature and environment groups as a key stakeholder.

5.8 Time and Timing

It is well known that many underground infrastructures are built out of necessity – when there is no other choice but to go underground. Very often, the cost of such construction is very high due to the congestion and extensive existing buildings. On the other hand, the cost of construction can be much lower in areas where there is relatively little development. However, investing early requires a very long-term view on the part of the planner and decision maker – to go underground when we do not have to. Timing is a key factor.

Construction cost can be minimized when there is little development in the surrounding area, and the contractor has the freedom to choose the most economical means for construction. There is also more freedom in planning the depth and alignment.

On the other hand, construction in congested areas become much more expensive due to the constraints imposed in safety, structural stability, and environmental control. In addition, construction activities often create secondary traffic congestions and other environmental effects such as dust and noise, ground water drawdown and ground settlements, which are almost certain not included in the cost and benefit analysis in early decisions. However, it is easier to justify the more expensive choice because there is no other way. Hence the fundamental question of timing – should we invest and build underground when we do not have to go underground?

The concept of time and timing is thus important in underground space development because most underground space development has a long time span, and the timing of development has strong influence on the cost and thus the decision process. The number of parameters and boundary conditions will depend on the planning time horizon. Many of these parameters and boundary conditions are also dynamic and change with time. That is why scenario planning is important, because it allows the planners to test the system response (e.g. cost) to different boundary conditions. What is optimum now may not be the optimum in the long term, and different time horizons will likely lead to different optimum solutions. It is therefore important that the planning agencies take a long-term view in evaluating the development options.

5.9 Specific Uses and Planned Space Creation

In the Singapore, land reclamation can be done without any specific use identified for the land. On the other hand, almost all decisions on cavern development are based on identified specific uses. While such facilities have very good fit-for-purpose value, they often come with very high price tags because of lack of scale and a high percentage of preliminary work and basic support infrastructure such as access and power supply. On the other hand, if large-scale underground cavern space can be developed by aggregation of demand and clustering, the cost of construction per unit space can be significantly lowered due to the economy of scale and shared common infrastructure. In areas where the rock quality is suitable, this can be combined with underground aggregate mining, which can further lower the cost of cavern construction. In other countries, underground aggregate mining by itself is a viable business (Barbaccia, 2005; Ellefmo, 2006; Foster, 2006; Woodard, 1980), and the space created as a by-product is essentially free (Zhou, 2014; Zhou and Zhao, 2016). Additional cost may be incurred for long-term stability and other technical requirements but these costs are incremental should be minimal as a percentage of the overall infrastructure cost. The key challenge here is to establish an underground aggregate mining operation with the long-term objective of creating rock cavern space, without specific uses identified at the beginning, as is the case of all infrastructure projects.

6. CONCLUSION

While land has always been recognized as a constraint by the Singapore government, use of underground space only became part of the overall economic strategies in 2010, when the government Economic Strategies Committee made specific recommendations on underground development. With this, the use of underground space has been elevated to a strategic level and become an economic imperative. However, uunderground space development is a complex system and presents many challenges, including justifying the cost, 3D planning, coordination and integration, legal and administrative barriers, safety regulations, and managing public perceptions, among others. A top-down and whole-of-government approach, coupled with long-term strategic planning, is important to minimize the cost of underground construction and to optimize the use of underground space as part of the sustainable urban development.

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