CREATION OF SPACE IN ROCK CAVERNS IN SINGAPORE — PAST, PRESENT AND FUTURE

Lui Pao Chuen[1], Zhao Jian[2,4] and Zhou Yingxin[3]

[1]*National Research Foundation, Prime Minister's Office, Singapore.*
E-mail: LUI_Pao_Chuen@mfa.gov.sg

[2]*Ecole Polytechnique Fdrale de Lausanne (EPFL), Switzerland E-mail: jian.zhao@epfl.ch*

[3]*Defence Science and Technology Agency (DSTA), Singapore. E-mail: zyingxin@dsta.gov.sg*

[4]*Nanyang Centre for Underground Space, Nanyang Technological University, Singapore.*

Systematic study of rock cavern developments started in Singapore around 1980s, with feasibility studies for different applications. Construction of the first cavern project, the Underground Ammunition Facility (UAF), began in 1999 and commissioned in 2008. The second cavern project, the Jurong Rock Caverns (JRC) for hydrocarbon storage below the seabed, will begin operation in 2013. The development of an Underground Master Plan is in progress. Greater use of underground space in Singapore can be expected in the future to meet the needs of a growing population.

Keywords: Underground space; Rock cavern; Underground master planning.

1. OVERVIEW OF SINGAPORE

With its land area of 710 km^2 and a total population of over 5 million, Singapore is one of the world's smallest and most densely populated countries. Singapore is also one of the most developed economies and wealthy nations. Continuing economic development and rapid population growth have led to increasing demand for land space, as shown in Table 1.

Some of the solutions to increase land space are land reclamation, high-rise building, and extensive use of deep basements and tunnels. Land reclamation has been the primary mean for increasing the total land area of Singapore. Basement of high-rise buildings is a norm in Singapore. They are often used as basement carparks and shopping centres.

Nearly all the metro lines in Singapore are underground. The newest metro line announced in September 2012, the Thomson Line, will be 30 km long and will have 22 stations. Tunnels are also extensively used in road transport. Major expressways with substantial underground segments are the Central Expressway, the Paya Lebar Expressway, and the Marina Coastal Expressway currently under construction.

Utilities are the other major users of underground space. They include the Common Service Tunnels at the Marina Bay area, the Deep Tunnel Sewer System (DTSS) Phase 1, and the recently announced 35 km long Cable Tunnels for power distribution.

Advances in Underground Space Development – Zhou, Cai & Sterling (eds)

Published by Research Publishing
ISBN: 978-981-07-3757-3 :: doi:10.3850/978-981-07-3757-3_key2

Table 1. Land use distribution in Singapore 1960–2000.

Year	Land Area, km^2	Build-Up, km^2	Agriculture, km^2	Forest, km^2	Marsh & Tidal Waste, km^2	Others (water, open space, gardens, cemeteries), 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 Estimate	714.3	418.4	9.3	28.6	15.7	238.2

Source: "Limits to Growth: Population, Density and Urban Stress" by Malone-Lee Lai Choo.

Singapore is of moderately low relief. Most of the land areas are at 10-30 m above the mean sea level. The area of highest relief is at the north-central part, where the highest hill (the Bukit Timah) is at 163 m above the mean sea level.

The Granite Formation is the base rock of the Singapore Island. The granite, termed in Singapore as the Bukit Timah granite, can be seen in the central and north part. The west part is covered by sedimentary rocks, the Jurong Formation, speculated to be up to over 500 m thick, and the east covered by consolidated alluvial deposits, the Old Alluvium, of up to 200 m thick. The simplified geology layout of the Singapore Island is shown in Figure 1, along with locations of the most recent geological investigations.

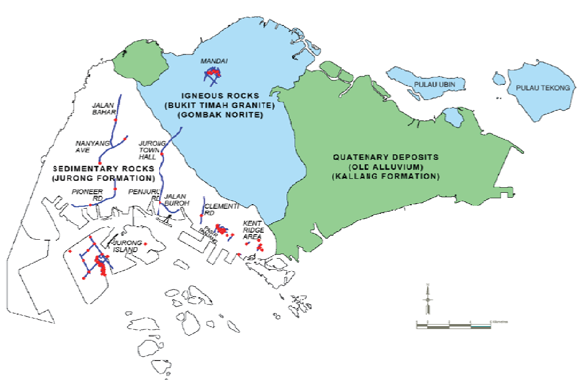

Figure 1. Simplified geological map of Singapore, showing some geological investigation locations (after Sharma *et al.* 1999, Zhou and Cai 2011.

The massive and hard Bukit Timah granite has been proven to be an ideal rock for cavern construction. The Jurong Formation in the west consists of some good quality sedimentary rocks, mainly sandstones, siltstones and limestones, which are considered as suitable medium to host rock caverns. The Old Alluvium covering much of the east region is not suitable for rock caverns, but the granite below, in some locations only a few tens of meters, are massive and ideal for building cavern at depth, below the alluvium cover.

2. PAST AND PRESENT ROCK CAVERN DEVELOPMENT

Table 2 summarises the major activities related to rock cavern development in Singapore. The study of underground space in rock cavern started in 1980s (Broms, 1989). A series of feasibility studies completed in 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

Table 2. Major activities on rock cavern development in Singapore since 1990.

Period	Major Activities and Development
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.
2007–2012	JRC (Jurong Rock Caverns for hydrocarbon storage) construction started in 2009
	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

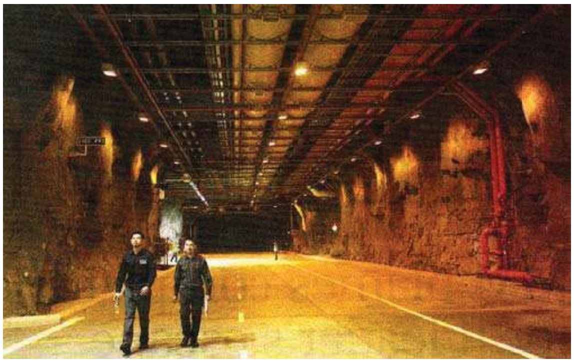

Figure 2. Underground Ammunition Facility (UAF) cavern after excavation (The Straits Times 2008).

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 2). 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.

With the shortage of industrial land at the Jurong Island, the use of rock caverns for oil and gas storage is an attractive option. JTC initiated feasibility studies on developing rock cavern storage for hydrocarbons in the Jurong Island 2000. Researchers from NTU provided research and scientific support. The first study located the storage caverns directly below the Jurong Island. This would however require acquisition of the surface land. Locating the caverns below the seabed overcomes this need. Construction of the Jurong Rock Caverns (JRC) began in 2007. The JRC is a cavern complex with cavern span typically 20 m wide and at about 130 m below the seabed, in the sedimentary rocks of the Jurong Formation (Figure 3). The current phase will provide a storage capacity of 1.5 million m3 and the total planned storage of the project is 3 million m^3.

The Underground Science City (USC) was initially explored by JTC with researchers from NTU between 1998 and 2000 (Zhao *et al.* 2001).A feasibility study by Amberg Engineering and Jurong Consultants (Figure 4) completed recently had found the project to be

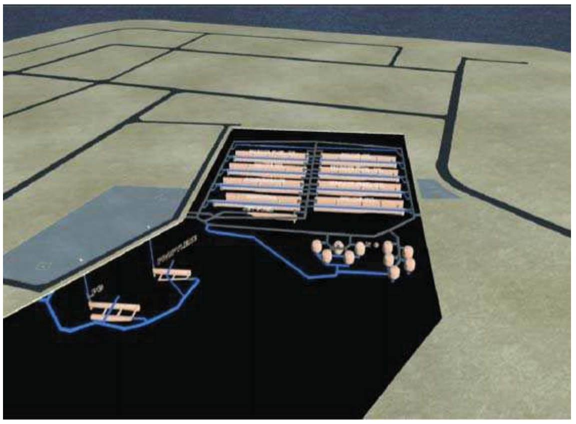

Figure 3. The Jurong Rock Caverns (JRC) under construction (Courtesy of JTC and SINTEF-Tritech-Multiconsult Consortium).

Figure 4. Architect's impression of the Underground Science City (USC) at Kent Ridge (Courtesy of JTC, Amberg Engineering and Jurong Consultants).

technically feasible. Located underneath the Kent Ridge Park, between Science Park 1 and Science Park 2, USC is designed to provide about 200,000 m^2 of space for research and scientific activities (The Business Times 2009). The project is under evaluation on economic viability.

3. FUTURE ROCK CAVERN PROJECTS

With significant economic and social developments and population growth, the demand for land is expected to exceed the supply. Data from the Urban Redevelopment Authority (URA) shows that Singapore's land area has grown from 660 km^2 in 2001 to about 714 km^2 in 2012. The Concept Plan 2001 had projected the land demand for a population of 5.5 million in 2040-2050 to be 800 km^2 (Table 3). Today, Singapore's population stands very near 5.5 million while the available land is only 714 km^2. Assuming the land use projection remains, there is an actual shortfall of about 86 km^2 (or 8,600 ha).

Table 3. Projected land use demand and distribution in Singapore's Concept Plan 2001 (URA 2001).

Land Use	Existing Area, Ha (%)	Demand Projection, Ha (%)	Difference, Ha
Housing	10,000 (15.1)	19,000 (22.5)	8,000
Commerce	1,000 (1.5)	1,500 (1.9)	500
Industry	8,000 (12.2)	14,000 (17.5)	6,000
Parks	2,500 (3.8)	4,500 (5.6)	2,000
Community and institution	4,000 (6.0)	5,500 (7.8)	3,000
Sports and recreation	1,600 (2.4)	2,000 (2.5)	400
Infrastructure and utilities	3,300 (5.0)	6,300 (7.8)	3,000
Roads	8,200 (12.5)	9,600 (12.0)	1,400
Others (Undeveloped land, reservoirs, cemeteries, & special use)	27,400 (41.5)	18,600 (23.2)	−8.800
Total	66,000 (100)	80,000 (100)	14,000

Source: URA website. The concept plan is reviewed every 10 years.

The use of underground space to enhance the land use to secure future growth was highlighted in the Economic Strategies Committee report in 2010 (ESC 2010): "In the next 10 years, the Government should seek to catalyse the development of underground space as a means to intensify land use" and to "expand our 'land bank' by investing in the creation of underground space". Indeed, some of the demands, particularly those by industry, transport and infrastructures can be met by using underground space. Rock caverns will be an inevitable feature of future Singapore to maintain the current level and greenery. The use of rock caverns will be in various forms, ranging from industrial to recreational, such as hydrocarbon storage, warehouse and logistics, data centre, energy production, incineration plant, factory and workshop, sewage and water treatment, water storage and storm water retention, sport complex, library and learning complex, R&D laboratory, transport station and depot. The increase use of underground space will help Singapore to achieve a high standard of living and economic growth.

An example for the use of underground caverns is the proposed development of large cavern complex to capture storm water in the wet seasons for supplement to other water sources during dry seasons (Lui 2012) (Figure 5). Water storage caverns can be connected to storm water tunnels for storm water retention and water collection.Connecting the surface reservoirs with the underground reservoirs will allow energy storage withpumped-storage hydoelectricity (PSH).The cost of construction can be mitigated with the sale of the excavated granitic rocks for use as aggregates.

The Nanyang Centre for Underground Space (NCUS) at NTU is currently conducting an underground space master planning exercise at the NTU campus. The campus at Yunnan Garden has a typical topographic feature of Singapore and the master planning study is to be a test bed for the underground space master planning for the nation.A similar exercise on the development of a underground master plan is being done in the Kent Ridge campus of NUS.

Recently, the Ministry of National Development (MND) and the Urban Redevelopment Authority (URA) have initiated R&D calls related to space creation and sustainable urban living, and specifically highlighted the need of underground space creation.

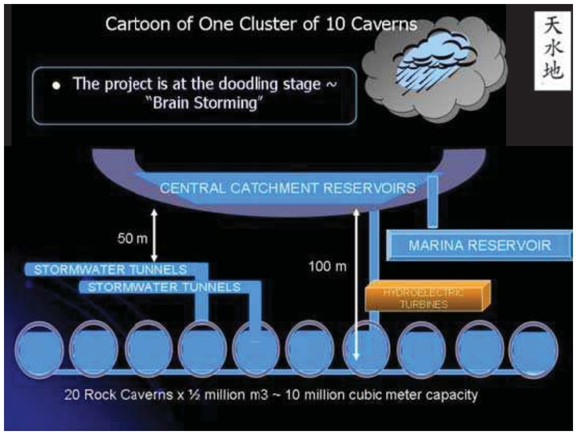

Figure 5. Conceptual use of rock caverns for water storage and stormwater retention and pumped storage hydro-electricity scheme (after Lui 2012).

4. MASTER PLANNING, SYSTEM APPROACH AND SPACE INTEGRATION

Demands for land space for industrial development and demands for living places are always in conflict. To cope with the demands of space for sustainable economic and social developments, Singapore is developing a master plan for underground space use. The needs and benefits of master plan have been summarized by Zhou and Cai (2011):

(i) Underground space is one of the natural resources underground (others being minerals, groundwater, and geothermal energy). The use of underground space must be planned to derive the maximum benefits to society in a sustainable manner.

(ii) Underground space is three dimensional. It is beneath the ground and cannot be easily visualized (Tor *et al.* 2005). However, underground space can be developed in layers at different depth. Therefore zoning of underground space can be done both horizontally and vertically.

(iii) Unlike surface buildings, underground structures cannot be "taken down" once developed. Conversion of rock cavern usages usually requires substantial provision for the necessary supporting infrastructure. It therefore needs a more long-term planned development approach.

(iv) Underground space always needs surface access and connections, including fire and emergency exits. Underground space planning therefore must be linked with surface plan exercises, to ensure that exits and connections are allowed for future underground space development.

(v) Type and usage of underground space is often influenced by the geologic and hydrogeologic conditions of the underground materials. Subsurface conditions need to be explored and known so that underground space planning can match the subsurface conditions.

The future development of underground space must be considered in the context of space integration, taking the system approach. Spaces in Singapore, land, sea, air, and underground should be considered as one system. As the height constraints around airports limit the full development potential of the surrounding lands, the release of the height constraints will lead to the development of higher buildings. Land reclamation is a system approach of integration of sea and land spaces. However, land reclamation needs to work within the need for marine space. Underground space should also be considered as a space that can be integrated and as a part of the space for sustainable urban living. It should be noted that underground space is unique asit has the 3D nature, i.e., below the same land plot, underground space can be developed in layers and for very different usages, e.g., car parks and shopping malls in basements at shallow depth, libraries and R&D facilities in shallow rock caverns below, warehouse and logistic caverns further down, and at farther depth, caverns can be used as data centres, and for Wafer Fab factory (which is being built in Switzerland).Through integration, it is likely to see the coupling and integration of land and underground space development for better living, working, learning and playing.The models are not there yet and the system approach, by integrating various parts, will certainly help to develop a better model over the time.

The Straits Times (2012) in a recent article titled ″Underground, the next frontier for Singapore″, highlighted that ″Singaporeans may one day live, work and play in vast, subterranean caverns that make today's underground malls look like home basements″. Dr John Keung, CEO of Singapore's Building and Construction Authority, was quoted as saying ″Of course you can build up, but there is a limit, because we have airports. You can reclaim, but there is also a limit, as you need to keep fairways and anchorages for your port. The only thing left is to go underground″ (The Straits Times 2012). His statement is a clear indication of the direction that Singapore is heading in the creation of subterranean space.