Advances and Challenges in Underground Space Use in Singapore

Based on Keynote Lecture presented at ACUUS 2016 St Petersburg

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SRMEG Networking Night
13 January 2017

The Land and Population Squeeze

<table>
<thead>
<tr>
<th>Land and Population</th>
<th>Year 2014</th>
<th>Year 2030</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land size</td>
<td>716 km²</td>
<td>766 km²</td>
<td>50 km² (7%)</td>
</tr>
<tr>
<td>Population</td>
<td>5.5 mil</td>
<td>6.5-6.9 mil</td>
<td>1-1.4 mil (18-25%)</td>
</tr>
</tbody>
</table>

Based on data from URA 2013 Land Use Plan and National Population and Talent Division, 2013

Significantly, no other city in the world has to cater to defence needs (land use) like Singapore
This land use plan includes future land to be created.

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### 2013 URA Land Use Plan

This image is a map indicating land use plans for Singapore, with color-coded areas representing different land uses.

### Land Use Plan (URA 2013)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Planned Land Supply (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Housing</td>
<td>10,000 (14%)</td>
</tr>
<tr>
<td>Industry and commerce</td>
<td>9,700 (13%)</td>
</tr>
<tr>
<td>Parks and nature reserves</td>
<td>5,700 (8%)</td>
</tr>
<tr>
<td>Community, institution and recreation facilities</td>
<td>5,400 (8%)</td>
</tr>
<tr>
<td>Utilities (e.g. power, water treatment plants)</td>
<td>1,850 (3%)</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>3,700 (5%)</td>
</tr>
<tr>
<td>Land transport infrastructure</td>
<td>8,300 (12%)</td>
</tr>
<tr>
<td>Ports and airports</td>
<td>2,200 (3%)</td>
</tr>
<tr>
<td>Defence requirements</td>
<td>13,300 (19%)</td>
</tr>
<tr>
<td>Others</td>
<td>10,000 (14%)</td>
</tr>
<tr>
<td>Total</td>
<td>71,000 (100%)</td>
</tr>
</tbody>
</table>

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Challenges in Land Reclamation

22% of Singapore’s land is reclaimed

Issues
• Water depths and boundaries
• Sand supply and cost
• Environmental concerns
• Geopolitics

Sand and Sand, Everywhere

2030. The sand stockpiles are to safeguard supplies. Singapore long ago ran out of its own and became, according to a report published last year by the United Nations Environment Programme, by far the largest importer of sand worldwide and, per person, the world’s biggest user. But, one by one, regional suppliers have imposed export bans: Malaysia in 1997, Indonesia ten years later, Cambodia in 2009 and then Vietnam. Myanmar also faces pressure to call a halt. Exporting countries are alarmed at the environmental consequences of massive dredging. And nationalists resent the sale of even a grain of territory.

Singapore is unusual both in being so small that such a large proportion of its territory is man-made, and in being so close to its maritime neighbours, Malaysia and Indonesia. Not only has it faced criticism from environmental groups because of the impact its sand purchases have had in the exporting countries, in 2003 it also faced a legal challenge under the UN Convention on the Law of the Sea (UNCLOS) from Malaysia over land-reclamation projects at either end of the Johor Strait that separates the two countries. Malaysia alleged the work was impinging on its sovereignty, harming the environment and threatening the livelihoods of some of its fishermen.

Ref: The Economist, 6/26/2015

Such quantities of sand
Singapore's seagrass meadows at risk from reclamation
Half of Singapore's only flowering sea plants killed in the last 50 years.
Saturday, Jul 12, 2014

- A National University of Singapore (NUS) study has found that filling the island's coastal waters with sand over the almost five decades since independence has killed 1.6 sq km of seagrass - nearly half of the country's total.


Sustainable urban development: Do we need to worry about our seagrass?

Underground Space – the new Frontier!

Use of UG space was elevated to a strategic level by Spore government Economic Strategies Committee (ESC) in 2010
Invest in Creating and Using Underground Space

*ESC recommends that the government acts early to catalyse the development of underground space by..*

- Creating basement spaces in conjunction with new underground infrastructural developments
- Developing an underground master-plan
- Establishing a national geology office to collate underground information
- Developing a subterranean land rights and valuation framework to facilitate underground development; and
- Investing in underground development R&D and directly investing in cavern level test-beds.


Important Development

- New legislations on ownership and acquisition of underground space

- Paradigm shift:
  - *Underground as the default option for major utility and infrastructure.*
  - *Agencies will have to justify not going underground*
New Laws on UG Space

State Land (Amendment) Act 2015
• Land includes only so much of the subterranean space as is reasonably necessary for the use and enjoyment of the land, either:
  – Specified in State title; or
  – 30m below Singapore Height Datum

Land Acquisition (Amendment) Act 2015:
• Allows government purchase of specific layers of underground space below private land

MAJOR UNDERGROUND INFRASTRUCTURE AND STORAGE FACILITIES
The depot provides stabling of the trains, maintenance and ops control of the Circle line. The depot has a capacity for 77 trains and has an area of 100,000 m². At 1km long in the east-west direction and approximately 150m wide at mid-point, the depot is situated 20 meters below ground at track level.
The DTSS Ph I comprises a 48 km tunnels stretching from Kranji to Changi, an UG water reclamation plant with a capacity of 800,000 m³ per day, a 5 km sea outfall at Changi, and some 60 km of link sewers.

**DTSS - The Deep Tunnel Sewage System**

DTSS Ph II being planned now

DTSS Ph2 will comprise of the South Tunnel and its network of link sewers, leading to a water reclamation plant at Tuas and another deep sea outfall. The project is envisaged to be developed before 2030.

**Cable Tunnel Project (Under Construction)**

Length: 35 km (18.5 km N-S and 16.5 km E-W)
Internal diameter: 6 m. 14 utility buildings.

Cable tunnel from Pioneer Road to Jurong Island Power Station being planned (SP, 2015)
Immersed Cable Tunnels

- Seraya tunnel: 2.6 km. $168 mil (1985 contract price)
- Tuas tunnel: 2.1 km. $130 mil (1996 contract price)

Reasons: It was cheaper!

The Tuas cable tunnel is about 13m below sea level at the top

Section of the Tuas subsea tunnel
Ref: Mainwaring et al., 2001, RETC

The CST is a “plug-and-play” format, with 100% emergency backup services and capacity for expansion

A network of tunnels that house and distribute utility services to all developments at Marina Bay. It also houses the world’s largest underground district cooling system

Commons Services Tunnel @ Marina Bay
Source: Singapore URA
Singapore’s ammo stored safely – underground

First major cavern facility in Singapore.
Land savings of up to 900 ha, (>1% of our land area)

Caverns 130m beneath seabed
- Total storage: 1.5 mil m³
- Ph2 being planned.
- Land savings = 60 ha

Jurong Rock Caverns for Oil Storage

Source: ACUUS 2012
UNDERGROUND PROJECTS UNDER PLANNING AND STUDY

The corridor concept incorporates many combined uses and integration, with cycling and pedestrian paths throughout the 21.5 km expressway, and vehicles mainly plying underground.

Car-free New Town Centre (Planning)

Tengah New Town will have Singapore’s first car-free town centre, set in lush parkland and with traffic running underneath the town centre.

The town will has 30,000 units of public housing and 12,000 units of private housing.

Underground Warehousing and Logistic Facility @ Tanjong Kling (JTC Study)

65 Caverns (GFA of 568,200 sqm)
110 m below ground surface

Source: ACUUS 2012
Inter-estates Goods Mover System (iGMS) Study by JTC

- An underground corridor of about 37 km that allows direct goods movement from various industrial estates (or distribution centres) to the future Tuas Port
- Possibility to extend to Changi airport in Eastern Singapore


UG aggregate mining will be combined with space creation

Source: PUB TENDER REF NO: 2P/33150147. DATE: 23 October 2015
Challenges

- Complexity
- Justifying the cost
- Finding the underground space
- Managing public perceptions and expectations
- Integration and coordination (across agencies, stakeholders, applications)
- Standards and regulations
- Building the right competency

Complexity of Underground Space Development

- Large scale in size and budget
- Long lead time
- Multi-disciplinary
- Large number and diverse types of components and sub-systems and stakeholders
- Dynamic
  - Multiple time scales
  - Requirements that change with geopolitical and economic development of the society

Complexity:
- Many independent variables interact unpredictably
- There is no right answer!
Justifying the Cost

• All these are very good but how much does it cost?
  – Whose cost (cost of traffic jams, road diversion, pollution)
  – When (UG construction is cheapest when you don’t have to)
  – How to quantify non-monetary benefits

It seems the easiest time to justify the cost is when you have no other solutions than UG!

We then collect cost data and perpetuate the perception that UG construction is expensive with these data

Why UG Space Can be Expensive

• Inherent limitations
  – Poor geological conditions
  – Construction in congested areas (existing aboveground and sometimes underground development)

• Non-technical reasons (may be more important)
  – Poor planning (rush into design and construction)
  – Wrong timing (re-active measures e.g. chasing traffic jams)
  – Lack of competency (outsourcing of engineering capability)
  – Inadequate policy or overly conservative regulations (regulators bear no responsibility for the schedule or cost)
Costs of Tall Buildings and Rock Caverns

Rock excavation cost: S$130/m³ in good rock (L2NIC 2nd call for R&D). Factor in M&E and C&S, the cost is about double. This would work out to be S$1040/m² (or about US$800/m²) equivalent gross internal area based on 4-m cavern height. **Sales of rock and land cost not included**

Ref: CTBUH Journal, 2010 Issue III

Ref: Langdon & Seah, 2014

**Comparison of worldwide rock tunnel cost**

Approximate costs for tunnel excavation and support (1999 US$). Costs do not include concrete lining, tunnel fittings, or tunnels driven by TBM

Ref: Hoek, Terzaghi Lecture, 2000
Tunnelling Cost in Soft Ground and Hard Rock for Mechanised Metro Tunnels in North America

Soft ground Avg: US$62m/km

Hard rock Avg: US$25m/km

Typical MRT tunnel size

Estimates for Thomson Line C&S (S$50-65m/km)

Spore granite ($130/m³)

Ref: Rostami et al., TUST 33 (2013)

Time and Timing

• When to invest?
• What is a good time horizon for long-term planning?
• From a construction cost point, the best time to develop underground is when we don’t have to, and when there is little aboveground development

• Systems thinking also requires us not to ask for immediate results: “Take a Panadol and wait for an hour”
Finding the UG Space
* 3D geological data
* Existing UG infra (the UG may already be crowded)
* Ownership of land above and below
* Entrance to underground (flat terrain an thick soil cover)

Public Perceptions
through which transport corridors may be placed. The Nature Society believes that engineering investigation and construction works for the Cross Island Line will severely degrade pasture habitats within the nature reserve and recommends that the design alignment be adjusted to avoid crossing the reserve.

Cross Island Line: Impact on nature to be studied. The Straits Times on Sept 12, 2013.
Misperceptions and Negative Associations

- Typical reaction: too expensive, dangerous . . .
- Also, we have too many “experts” who are too quick to express opinions or draw conclusions without proper studies.

“...One has to remember that this top half has to be cleared within eight to 10 hours in anticipation of the next rain or flooding. I can envisage that the storage capacity could be easily more than 100,000 cubic metres. Maybe 200,000 to 500,000 cubic metres would be the optimum size,” said Dr XXX, a senior member of the Institution of Engineers and assistant professor at the National University of Singapore. – CNA 17 June 2015

Standards and Regulations

- General lack of standards and regulations (Design methods, regulatory controls, blasting vibrations, structural inspection for rock caverns)
- Eurocode 7 for rock engineering design (currently a mess)
- Some regulations on deep excavation are very conservative and add to the construction cost
**Blasting Vibrations**

**Vibration Standards:**

<table>
<thead>
<tr>
<th>Country</th>
<th>PPV (mm/s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway/Sweden</td>
<td>18-70</td>
<td>Specifically stated for vertical PPV for different geological media. Corrections are made for other factors.</td>
</tr>
<tr>
<td>USA</td>
<td>50</td>
<td>Mostly based on US Bureau of Mines studies relating to surface mines</td>
</tr>
<tr>
<td>UK</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

**Singapore: 15 mm/s?**

**Some even imposed 5 mm/s**

**Other Issues:**
- Storage and transport safety
- Airblast near portals
- Noise and human annoyance

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**Observed Threshold Values (Micro cracking) For RC Structures**

<table>
<thead>
<tr>
<th>Material</th>
<th>Building Type</th>
<th>PPV (mm/s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light concrete</td>
<td>Residential</td>
<td>110</td>
<td>Structures expected to crack at 5-18 cm/s in predictions</td>
</tr>
<tr>
<td>Old concrete</td>
<td>Industrial</td>
<td>254</td>
<td>Initial concrete block cracks</td>
</tr>
<tr>
<td>Concrete with masonry foundations</td>
<td>Industrial</td>
<td>150-250</td>
<td>Tests showing lowest level corresponding to cracking</td>
</tr>
<tr>
<td>Concrete</td>
<td>Industrial</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Native stone with mortar joints &amp; rubble foundation</td>
<td>1 1/2-storey residential</td>
<td>180-510</td>
<td>Subjected to progressively more intense blast vibrations until damage was observed.</td>
</tr>
<tr>
<td>Walls</td>
<td>Residential</td>
<td>12.7</td>
<td>Door slams, Converted from strain</td>
</tr>
<tr>
<td>Walls</td>
<td>Residential</td>
<td>22.4</td>
<td>Pounding nails. Converted from strain</td>
</tr>
<tr>
<td>Walls</td>
<td>Residential</td>
<td>76</td>
<td>Daily environmental changes</td>
</tr>
</tbody>
</table>
### Relative cost for vibration control based on study for cavern excavation in Hong Kong

<table>
<thead>
<tr>
<th>Distance to structure</th>
<th>Allowable Peak Particle Velocity, mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 mm/s</td>
</tr>
<tr>
<td>10 m</td>
<td>750</td>
</tr>
<tr>
<td>20 m</td>
<td>350</td>
</tr>
<tr>
<td>50 m</td>
<td>200</td>
</tr>
<tr>
<td>100 m</td>
<td>150</td>
</tr>
</tbody>
</table>

Good to be safe, but there is a price to pay! Excessive conservatism is a waste of money!

Note: The curves are indicative only.

Source: Berthelsen, 1992

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### Building and Using the Right Competency

- Lack of local curriculum in tunnelling and rock engineering
- Lack of system engineering and cross-disciplinary education (too focused on engineering)
- Lack of engineering capabilities in government agencies
- Geotechnical engineering vs rock engineering practice
Strategies for Maximum Benefits

- Treating the underground as a strategic resource
  Master plan and early planning
- Co-ordination and Integration of
  - Various government agencies
  - Various underground infrastructure
  - The above- and under-ground
  - Defence & civilian uses
- Dual-purpose use
- Combining aggregate mining and space creation
- Developing local capability through R&D support

The Underground as a Strategic Resource

- Some uses are mutually exclusive while others can be combined
- Explore these possibilities with long-term view for sustainable development.
- Plan and coordination with both above- and under-ground
Underground Science City – Can we put it in the granite rock?

- Granite rock: cheaper to construction, possible underground quarrying to lower cost even more

Major National Initiatives

- **Underground Master Plan** Task Force (set up in 2007) to develop UG space plan and surface policy issues

- Building and Construction Authority Geology Office (set up in 2010) for *island geological investigation* to map out bed rock

- **Steering Committee for Underground Development** (set up in 2013)

- **Underground Works Department** under URA (set up 2014) to drive planning and development

- **Investment** in research and test bedding projects

Appointment of **Coordinating Minister for Infrastructure** (2015) a recognition of challenge and importance of coordination and integration
Underground Space Plan (Vertical Planning)

15m – 50m
To separate out living environments, build rather than blanket these that will cut through foot- and vehicle-traffic and walled underground. This reduces the risk of rain water and dust on homes.

100m onwards
The underground injection facility built under a quarry in Hanoi in 2006 stores ammonium and monosodium. It can be used to add about half the size of their Ria town. The living Rock Cairns under Living Island is also used to store water. Given rates, just two country are as high as zero storage, those countries very likely to be in water deficit.

1m – 3m
Underground pedestrian links will enable it rotate to connect Railways, MRTs, public and busy streets. For a more extensive underground pedestrian network, until others are considered, to fund the construction of external linkages in Orchard Road and the Central Business District.

1m – 10m
More than just water-saving measures, underground pipes and air proves to be a simpler and lower cost. The Cold Storage Tunnels in the Marina Bay is a creative way of supplying air and water to the rooms. The lines, up and down, with fewer maintenance enhancements on the roads.

20m – 50m
The Deep Tunnel Sewerage System is a tunnel that operates on energy and transmits sewage and waste water across the island. It includes Reclamation Plants.

Approval of RIE2020

• On 8 Jan 2016, PM approved Research, Innovation & Enterprise (RIE) 2020 plans
• $0.9b budget for Urban Solutions and Sustainability domain

Singapore commits record $19b to R&D

* The Research, Innovation and Enterprise (RIE) Council chaired by PM provides overall strategic direction for Singapore’s RIE. The national RIE plans and budget follows a 5-year cycle; the upcoming cycle, i.e. RIE2020, is for FY16 to 20.
Two major R&D initiatives
- MND Sustainable Urban Living: S$55mil funding (5 projects funded under 1st call in 2013)

Focus Areas
- Space creation (underground, floating platforms, elevated space)
- Optimising land use
- Creating highly livable residential towns
- Smart city and ICT support and platforms

Press Release, 3 Sept 2014:
The L2 NIC is the 2nd National Innovation Challenge. The first is Energy.

Combining Aggregate Mining with Space Creation

- Annual demand for 20mm aggregates in Singapore: 20 mil tons (equivalent to 12 mil m$^3$ excavated rock).
- If we meet 20% of this demand by underground quarrying, we would be excavating 2.4 m$^3$ of cavern space annually.
- This would also generate local economic activities.
### Summary of Selected Studies on Underground Aggregate Mining

Average price of granite aggregate in Singapore 2014: >$20/t
Assumed price of granite chips/quarry dust: $10/t

<table>
<thead>
<tr>
<th>Authors, Country</th>
<th>Aggregate Cost</th>
<th>Equivalent Cost for Space*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andrews 1998, Scandinavian countries and USA</td>
<td>US$4-$8/t</td>
<td>$6.4-$13/m³</td>
</tr>
<tr>
<td>Geer 2000, Australia</td>
<td>A$15.5-28.5/t</td>
<td>A$25-$45/m³</td>
</tr>
<tr>
<td>Brown, Coggan, and Evans et al. 2010, UK*</td>
<td>GBP£13-14/t</td>
<td>GBP20-22/m³</td>
</tr>
</tbody>
</table>

*One cubic meter of rock can produce about 1.6 tons of 20mm aggregates. The rest (about 40%) is in the form granite chips and quarry dust.

### Combining Space Creation with Aggregate Mining (UG Reservoir)

- Extraction ratio = 75%
- Total excavation vol = 55 mil m³
- Cost of excavation
  - Top heading = $100/m³
  - Benching = $40/m³
  - Average cost = $60/m³
- Profit from aggregate and quarry chips/dust
  - Aggregate selling price = $20/tonx1.6ton/m³=$32/m³
  - Chips and dust= $10/tonx1t/m³=$10/m³
  - Aggregate processing cost = $7/ton
  - Net gain = $32+10-7=$35/m³
- Net excavation cost = $60-35 = $25/m³
- Total net cost of excavation = $1.4 bil

A surface reservoir with 55 mil m³ at 5m depth would require 1,100 ha, or $22 bil at $2000/m². For commercial land at $10,000/m², land value would be $110 bil. Surface reservoir also loss about 1m/year of water from evaporation.
Conclusions

- Underground space use in Singapore is primarily driven by land use and has become a strategic and economic imperative.
- Major challenges include complexity, justifying the cost, finding the UG space, 3D planning, managing public perceptions, coordination and integration.
- A top-down and whole-of-government approach, coupled with long-term strategic planning, is key to minimising the cost of underground construction and to optimize the use of underground space as part of sustainable urban development.

Thank you!