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
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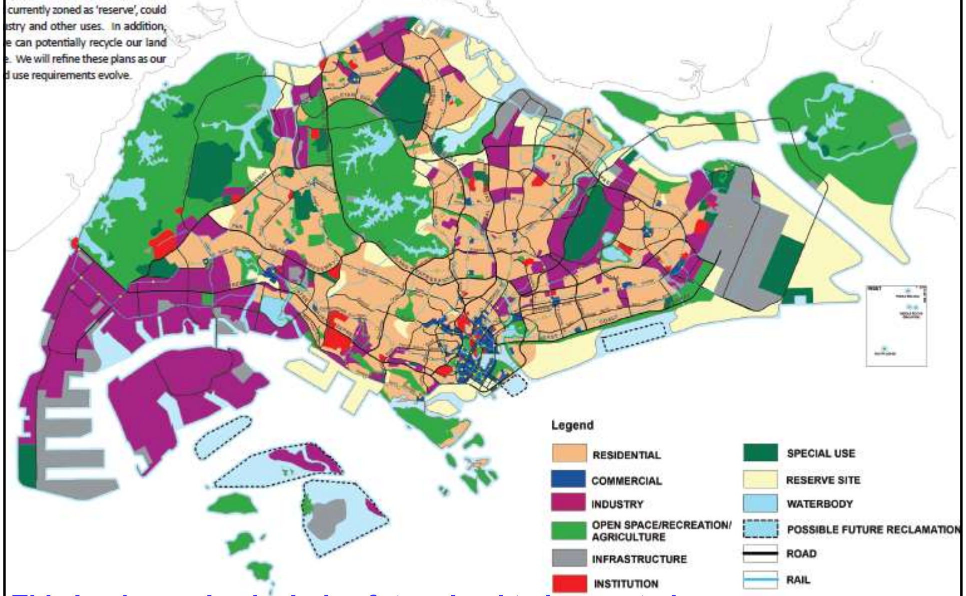
The Land and Population Squeeze

Land and Population	Year 2014	Year 2030	Increase
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%)

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

2013 URA Land Use Plan



This land use plan includes future land to be created.

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Land Use Plan (URA 2013)

Land Use	Planned Land Supply (Ha)	
	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%)

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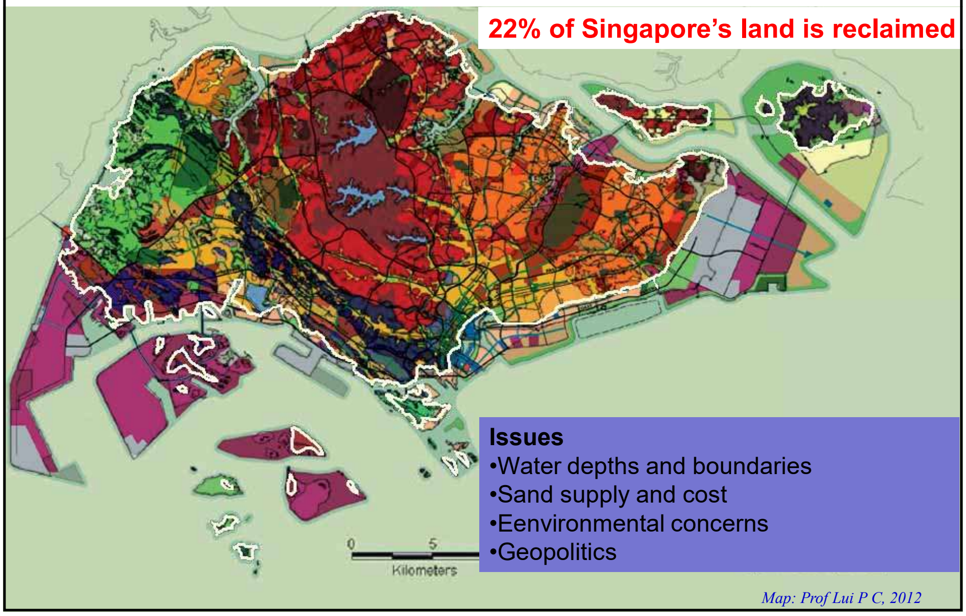
Challenges in Land Reclamation

22% of Singapore's land is reclaimed



Issues
- Water depths and boundaries
- Sand supply and cost
- Eenvironmental concerns
- Geopolitics

Map: Prof Lui P C, 2012

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.

The Economist

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

THE STRAITS TIMES

- 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.

Source:http://www.straitstimes.com/news/singapore/environment/story/singapores-seagrass-meadows-risk-reclamation.

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

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Underground Space – the new Frontier!

Use of UG space was elevated to a strategic level by Spore government Economic Strategies Committee (ESC) in 2010

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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.

-Singapore *Economic Strategies Committee Report (2010)*

Important Development

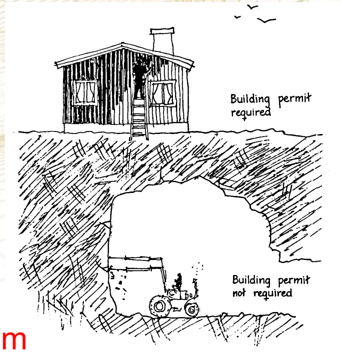
- New legislations on ownership and acquisition of underground space
- Paradigm shift:
  - *Underground as the default option for major utility and infrastructure.*
  - *Agencies will have to justify not going underground*

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

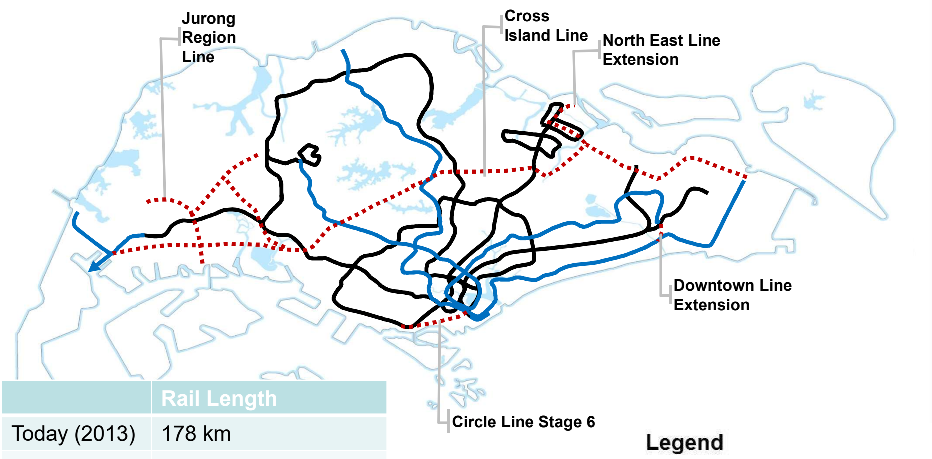


Land Acquisition (Amendment) Act 2015 :

•Allows government purchase of specific layers of underground space below private land

MAJOR UNDERGROUND INFRASTRUCTURE AND STORAGE FACILITIES

Rail Master Plan 2013, Land Transport Authority



	Rail Length
Today (2013)	178 km
By 2020	280 km
By 2030	360 km

All new lines are expected to be underground, including train depots

Legend
- Existing Rail Lines
- New Rail Lines by 2020
- New Rail Lines by 2030

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Source: Wen Dazhi

Kim Chuan Depot, largest underground depot in the world (*ref: Wikipedia*)

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.

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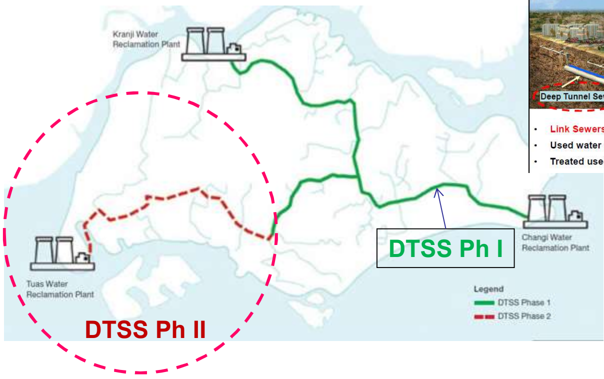
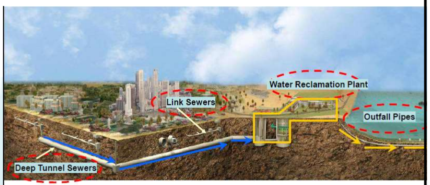
Source: Wikipedia

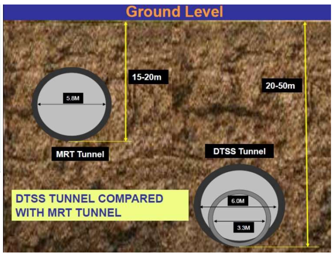
The **DTSS** Ph I comprises a 48 km tunnels stretching from Kranji to Changi, an UG water reclamation plant with a capacity of 800,000 m^3 per day, a 5 km sea outfall at Changi, and some 60 km of link sewers.

DTSS - The Deep Tunnel Sewage System





- Link Sewers convey used water from existing sewerage network to Deep Tunnel Sewer
- Used water flows by gravity to 2 centralised Water Reclamation Plants
- Treated used water discharge into Singapore Straits through Outfall Pipes



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.

Ref: PUB Website

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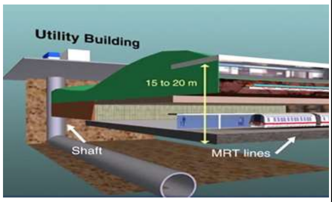
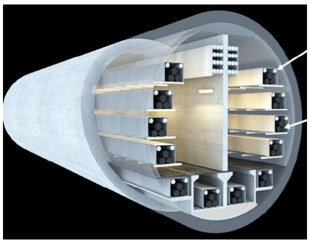
Cable Tunnel Project (Under Construction)

Length: 35 km (18.km N-S and 16.5km E-W)
Internal diameter: 6 m. 14 utility buildings.





Source: http://tunneltalk.com/Singapore-Sep12

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

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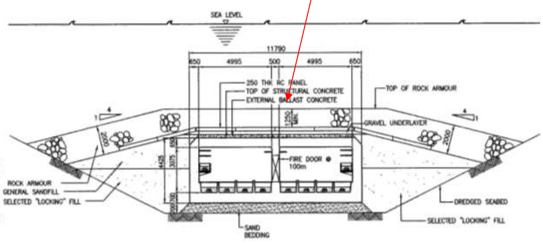
Immersed Cable Tunnels

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

Reasons: It was cheaper!

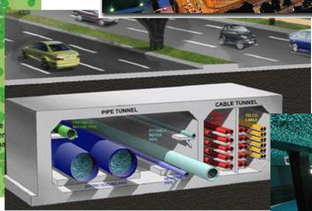
The Tuas cable tunnel is about 13m below sea level at the top



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

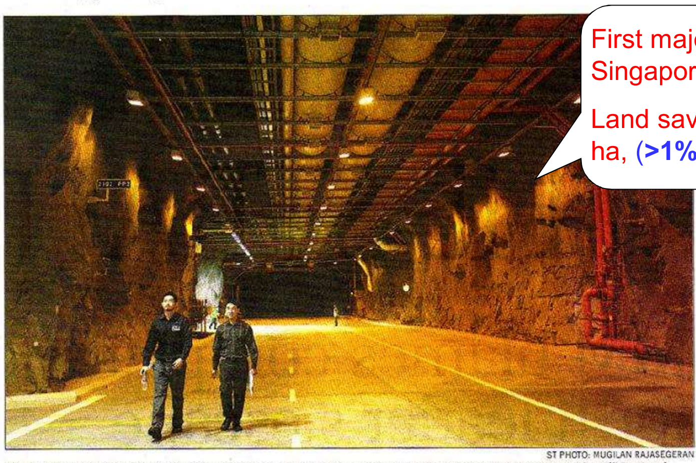


A network of tunnels that house and distribute utility services to all developments at Marina Bay. It also houses the world's largest underground district cooling system

Commons Services Tunnel @ Marina Bay

Source: Singapore URA

The Straits Times page 2 - Saturday 8 March 2008



ST PHOTO: MUGILAN RAJASEGERAN

COMPLEX WARREN: Two-lane wide roads, as seen here, at the SAF underground facility, link caverns where ammunition will be stored.

Singapore's ammo stored safely – underground

Opening of huge caverns at Mandai frees up space above

cles as large as container trucks will be able to move quickly through the complex.

Data from the Ministry of Defence said this ensures the

Expressway. For security reasons, Mindef did not reveal the number of caverns created, or how far down they lay.

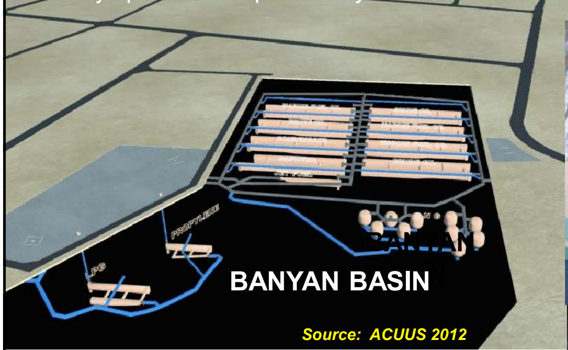
The rock-solid granite would

Technological University and consultants from Norway, Sweden and the United States and SembCorp Industries, which built the tunnels.

First major cavern facility in Singapore.

Land savings of up to 900 ha, **(>1% of our land area)**

The $950 mil Jurong Rock Caverns (JRC) was officially opened in Sept 2014 by Prime Minister Lee.



Source: ACUUS 2012

- **Caverns 130m beneath seabed**
- **Total storage: 1.5 mil m^3**
- **Ph2 being planned.**
- **Land savings = 60 ha**

Jurong Rock Caverns for Oil Storage

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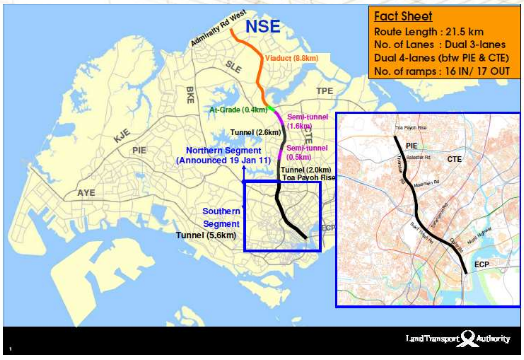
UNDERGROUND PROJECTS UNDER PLANNING AND STUDY

North South Corridor (Planning)



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

Ref: http://www.straitstimes.com/singapore/transport/north-south-integrated-transport-corridor-expected-to-be-completed-around-2026

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.

Straits Times: 9 Sept 2016

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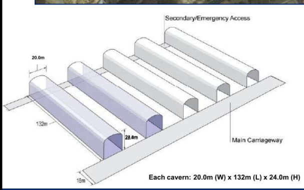
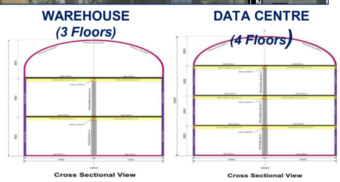
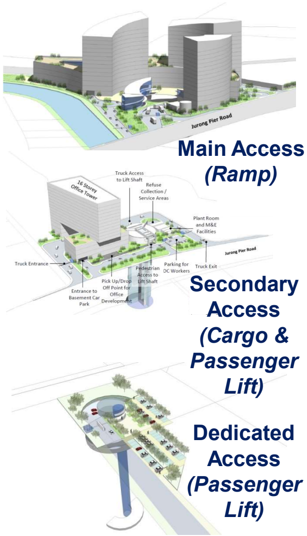
Underground Warehousing and Logistic Facility @ Tanjong Kling (JTC Study)

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







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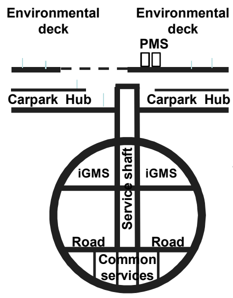
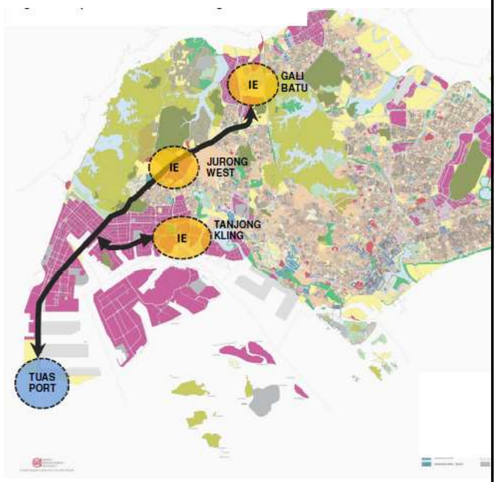
Source: ACUUS 2012

Inter-estates Goods Mover System (iGMS) Study by JTC



Concept SCHEMATIC



- 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

Source: JTC Tender: JTC 000/T/15B/2015. May 2015

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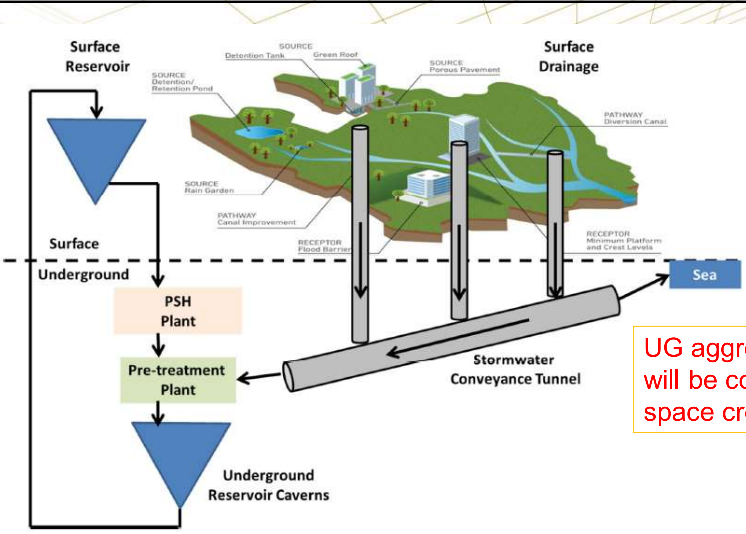

UG aggregate mining will be combined with space creation

eservoir System

- Future drainage and flood control
- Long term water storage
- Energy storage

PSH – Pumped Storage Hydropower

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

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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!

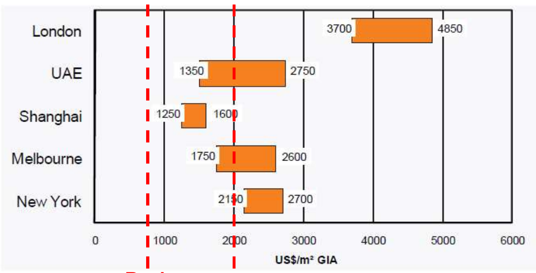
We then collect cost data and perpetuate the perception that UG construction is expensive with these data

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

Shell and Core High-rise Construction Cost Range (US$/m² GIA)



Ref: CTBUH Journal, 2010 Issue III

Rock excavation cost: S$130/m^3 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/m^2 (or about US$800/m^2) equivalent gross internal area based on 4-m cavern height. **Sales of rock and land cost not included**

CONSTRUCTION COSTS FOR SINGAPORE

Ref: Langdon & Seah, 2014

TYPES	OVERALL COST LOW S$/m²	OVERALL COST HIGH S$/m²
RESIDENTIAL		
Terraced Houses	2,500	2,800
Semi-Detached Houses	2,700	3,150
Detached Houses	3,150	4,200
Average Standard Condominium	1,950	2,200
Above Average Standard Condominum	2,200	2,950
Luxury Condominium	2,950	4,400
OFFICE		
Average Standard Offices	2,500	2,750
Prestige Offices	2,750	3,050
COMMERCIAL		
Shopping Centres, Average Quality	2,750	2,950
Shopping Centres, High Quality	2,950	3,250
Theatres / Cinemas (Excluding F.F.& E.)	2,050	2,300
CAR PARKS		
Multi-Storey Car Parks	950	1,350
Basement Car Parks	1,350	1,850

The above costs are at 4th Quarter 2013 levels.
For latest costs information, please refer to our 'L&S Quarterly Cost Publication'.

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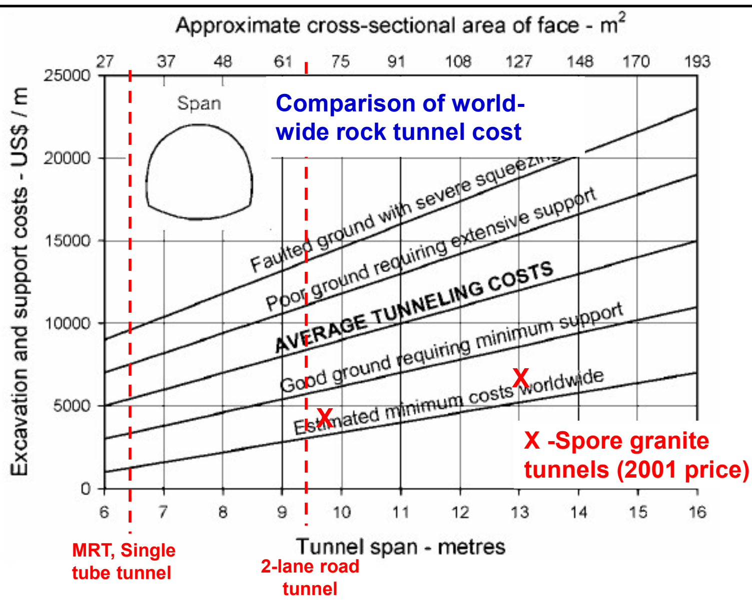

Approximate costs for tunnel excavation and support (1999 US$). Costs do not include concrete lining, tunnel fittings, or tunnels driven by TBM

Ref: Hoek, Terzaghi Lecture, 2000

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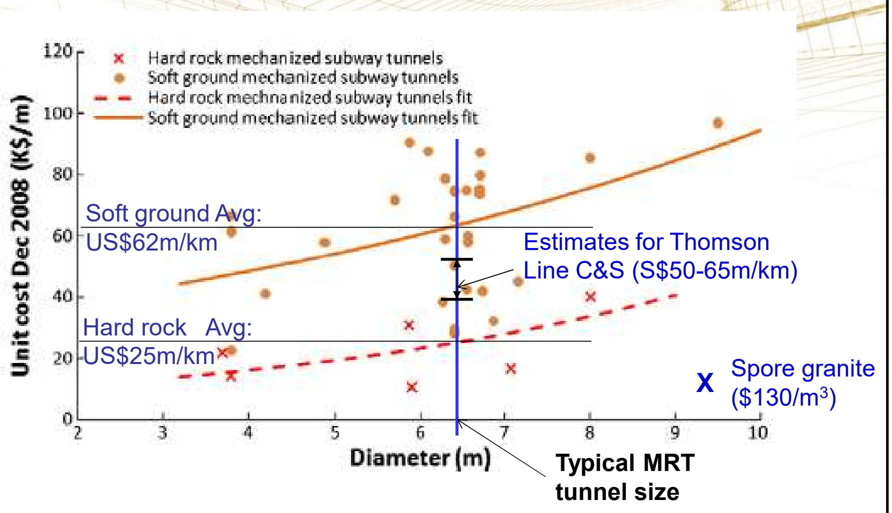
Tunnelling Cost in Soft Ground and Hard Rock for Mechanised Metro Tunnels in North America



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

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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”

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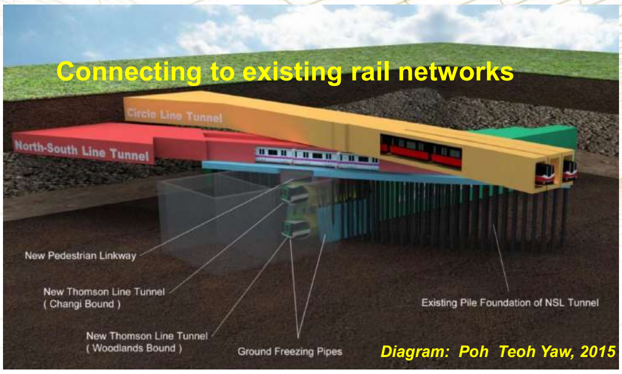

Finding the UG Space

* 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

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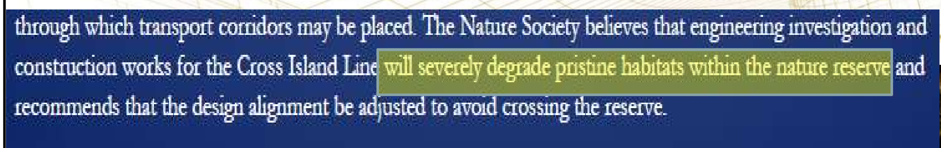
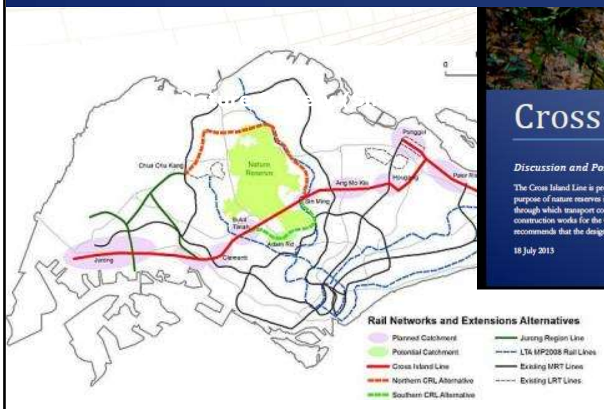
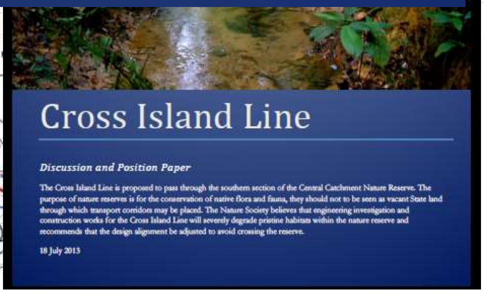
Public Perceptions







Cross Island Line: Impact on nature to be studied. **The Straits Times on Sept 12, 2013.**

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Misperceptions and Negative Associations

PRACTICAL PROBLEMS: Despite technological advances, building underground is inherently difficult. Extensive geotechnical studies and mapping are required, plus feasibility studies to ensure projects are viable.

Cost is another big factor, as depending on soil conditions, such developments can end up costing up to three times more than comparable surface structures.

Property consultant Knight Frank's managing director Danny Yeo feels cost considerations will restrict large underground developments to areas where land costs are high, like Orchard Road.

THE STRAITS TIMES (PAGE D4)
SATURDAY 6 FEBRUARY 2010

- Typical reaction: too expensive, dangerous . . .
- Also, we have **too many "experts"** who are to 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

News on Underground Reservoir System in Singapore

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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

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Blasting Vibrations

Vibration Standards:

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

Singapore: 15 mm/s ?

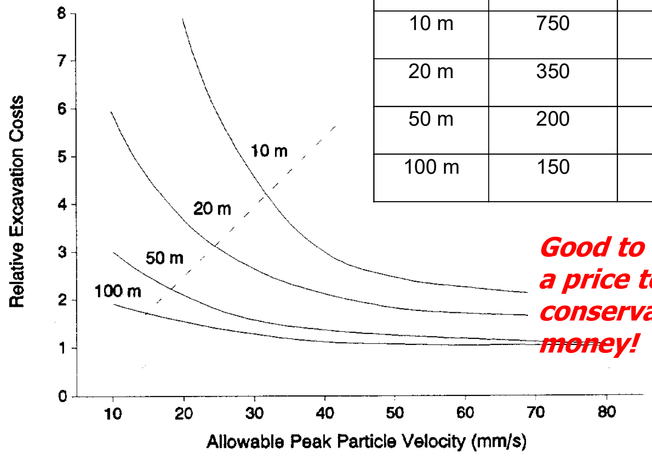
Some even imposed 5 mm/s

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

Observed Threshold Values (Micro cracking) For RC Structures

Material	Building Type	PPV (mm/s)	Remarks
Light concrete	Residential	110	
Old concrete	Industrial	254	Structures expected to crack at 5-18 cm/s in predictions
Concrete with masonry foundations	Industrial	150-250	Initial concrete block cracks
Concrete	Industrial	300	Tests showing lowest level corresponding to cracking
Native stone with mortar joints & rubble foundation	1 1/2-storey residential	180-510	Subjected to progressively more intense blast vibrations until damage was observed.
Walls	Residential	12.7	Door slams, Converted from strain
Walls	Residential	22.4	Pounding nails. Converted from strain.
Walls	Residential	76	Daily environmental changes

Relative cost for vibration control based on study for cavern excavation in Hong Kong



Distance to structure	Allowable Peak Particle Velocity, mm/s		
	20 mm/s	40 mm/s	60 mm/s
10 m	750	300	240
20 m	350	220	175
50 m	200	175	120
100 m	150	125	**100**

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

Source: Berthelsen, 1992

Note: The curves are indicative only.

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

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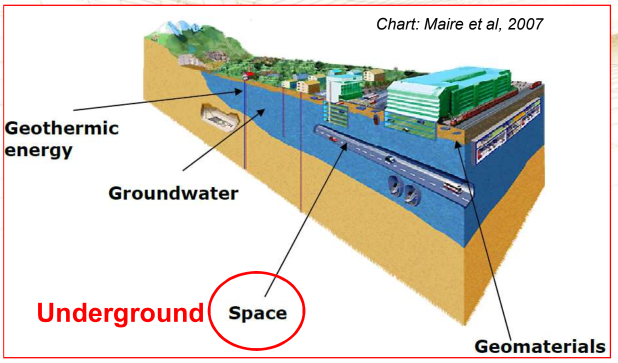
Strategies for Maximum Benefits

- Treating the underground as a strategic resource Master plan and early planning
- Co-odination 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

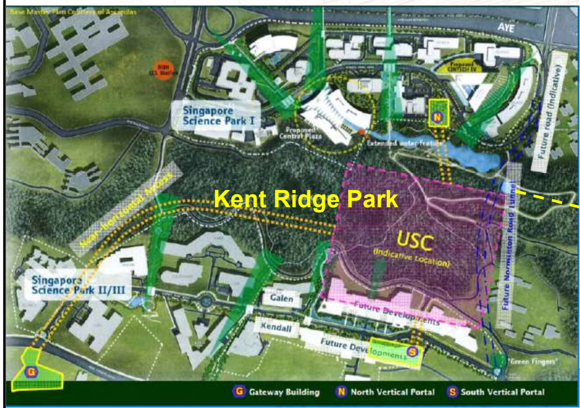
The Underground as a Strategic Resource

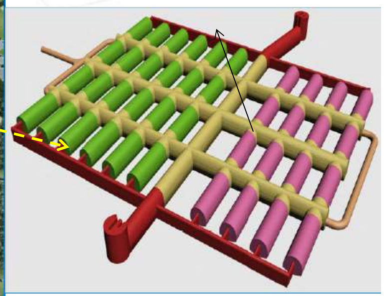


- Some uses are mutually exclusive **while others can be combined**
- Explore these possibilities with long-term view for sustainable development.
- Plan and coordination with both above- and under-ground

Underground Science City –
Can we put it in the granite rock?

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





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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

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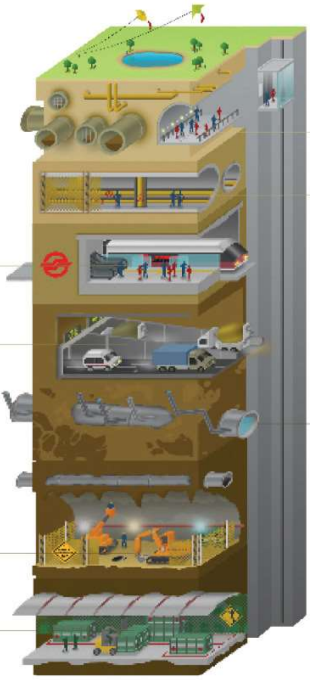
Underground Space Plan (Vertical Planning)



1m - 3m
Underground pedestrian links make it easier to connect between buildings or cross busy streets. For a more extensive underground pedestrian network, URA offers an incentive scheme to co-fund the construction of selected linkages in Orchard Road and the Central Business District.

1m - 10m
More than just space-saving measures, underground pipes are less prone to external wear and tear. The Common Services Tunnel in Marina Bay is a creative way of housing all utilities together. This frees up land, with lesser maintenance disruptions on the roads.

20m - 50m
The Deep Tunnel Sewerage System is a network of tunnels that operates on gravity, and transports sewerage and waste water across the island to two centralised water Reclamation Plants.

15m - 50m
To enhance our living environments, future major road and rail networks, especially those that will cut through built-up areas, will be located underground. This reduces the impact of noise and dust on homes.

100m onwards
The underground ammunition facility built under a quarry in Mandai in 2008 stores ammunition and explosives. It frees up land about half the size of Pasir Ris town. The Jurong Rock Caverns under Jurong Island is for petrochemical storage. In phase one, its five caverns are as high as nine storeys, saving approximately 60 ha of land.

URA, 2012

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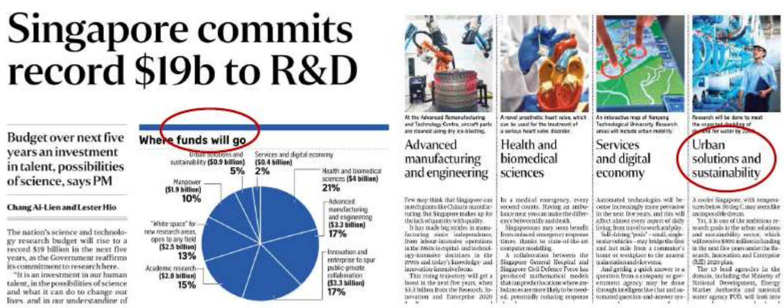
Approval of RIE2020

- 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

Budget over next five years an investment in talent, possibilities of science, says PM

Chang Ai-Lien and Lester Hio

** The **Research, Innovation and Enterprise (RIE)** Council chaired by PM provides overall strategic direction for Singapore's R&D. The national RIE plans and budget follows a 5-year cycle; the upcoming cycle, i.e. RIE2020, is for FY16 to 20.*

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Two major R&D initiatives

- MND Sustainable Urban Living. S$55mil funding (5 projects funded under 1st call in 2013)
- NRF Land and Livability National Innovation Challenge (L2 NIC) S$135mil funding for 5 years. Launched in Nov 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

The L2 NIC is the 2nd National Innovation Challenge. The first is Energy

Press Release, 3 Sept 2014:

MND SINGAPORE

NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE

FUNDS AWARDED FOR 10 PROJECTS SUPPORTED UNDER THE L2 NIC FIRST CALL FOR PROPOSALS

The Ministry of National Development (MND) and National Research Foundation (NRF), Prime Minister's Office, Singapore, today awarded 10 research projects a total of S$30.8 million in funding under the Land and Liveability National Innovation Challenge (L2 NIC) First Call for Proposals.

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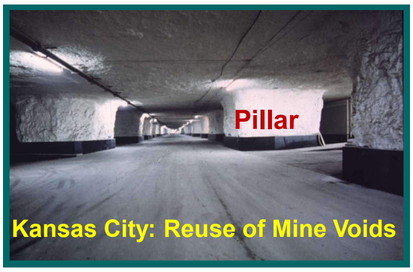
Combining Aggregate Mining with Space Creation

- 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



Photos: www.aggman.com/articles/may06a.htm

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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

Authors	Year of Study	Country	Aggregate Cost	Equivalent Cost for Space*
Andrews	1998	Scandinavian countries and USA	US$4-$8/t	$6.4-$13/m^3
Geer	2000	Australia	A$15.5-A$28.5/t	A$25-$45/m^3
Brown, Coggan, and Evans et al.	2010	UK*	GBP£13-14/t	GBP20-22/m^3
Benardos, Kaliampakos, et al.	2001	Athens, Greece	US$3.38/t	US$5.40/m^3

***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.**

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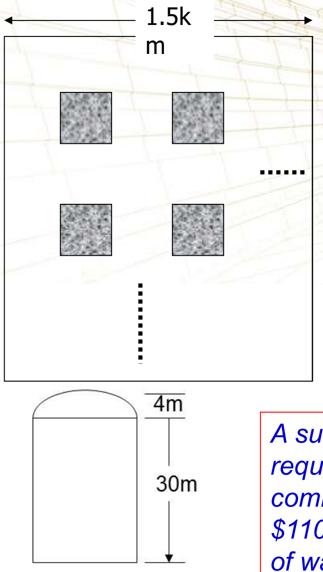
Combining Space Creation with Aggregate Mining (UG Reservoir)



- Extraction ratio = 75%
- Total excavation vol = 55 mil m^3
- Cost of excavation
  - Top heading = $100/m^3
  - Benching = $40/m^3
  - Average cost = $60/m^3
- Profit from aggregate and quarry chips/dust
  - Aggregate selling price = $20/tonx1.6ton/m3=$32/m^3
  - Chips and dust= $10/tonx1t/m3=$10/m^3
  - Aggregate processing cost = $7/ton
  - Net gain = $32+10-7=$35/m^3
- Net excavation cost = $60-35 = $25/m^3
- Total net cost of excavation = $1.4 bil

A surface reservoir with 55 mil m^3 at 5m depth would require 1,100 ha, or $22 bil at $2000/m^2 . For commercial land at $10,000/m^2 , land value would be $110 bil. Surface reservoir also looses about 1m/year of water from evaporation

Zhou Yingxin

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!