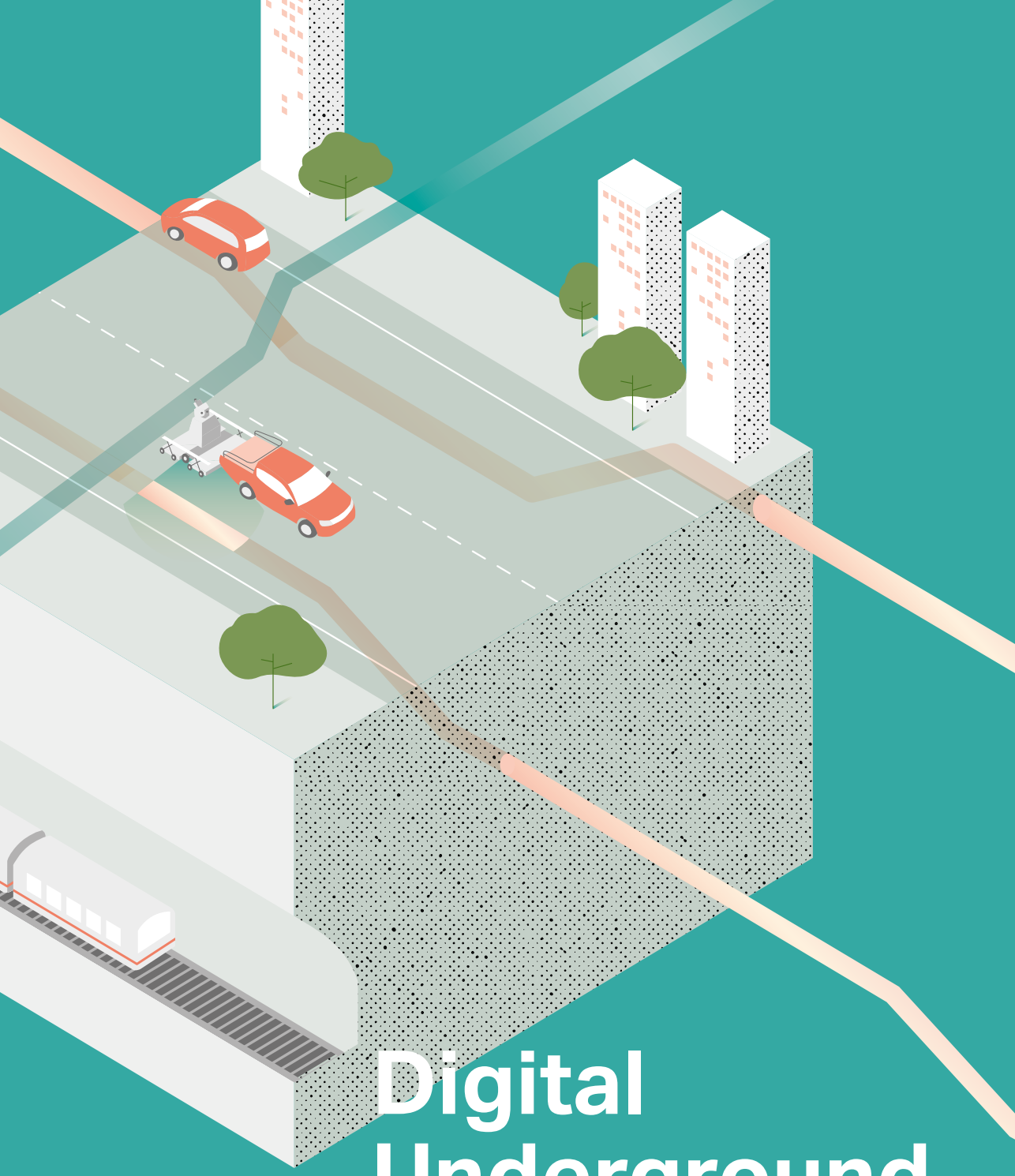

Digital Underground

Towards a Reliable Map of Subsurface Utilities in Singapore

Digital Underground

Towards a Reliable Map of Subsurface Utilities in Singapore

Edited by Dr Gerhard Schrotter and Rob van Son

This publication has been realised as part of the Digital Underground: 3D Mapping of Utility Networks project at the Future Cities Laboratory (FCL), established by ETH-Zurich and the Singapore National Research Foundation (NRF), and operating under the auspices of the Singapore-ETH Centre. The project is funded by the Underground-Related Studies and Projects Fund (USPF) of the Ministry of National Development of Singapore and is sponsored by Singapore Land Authority (SLA).

Preface

Dr Victor Khoo
Dr Gerhard Schrotter

Singapore, driven by land shortage, is increasingly opting for multi-layered and overlapping developments both above- and underground. Moving into the near future, as urbanisation intensifies Singapore and many other major cities will intensively use their underground space, so that more land above ground can be freed up for housing, parks and community use.

The need for spatial planning of the underground has been recognised and initiatives have started to document built infrastructure, such as utilities, located at shallow depths. These initiatives are mostly driven by the urgency to better plan, coordinate, and optimise the underground space and manage the huge financial value of the underground infrastructure. For example, in Switzerland the replacement value of the supply and disposal underground networks with a length of around 550,000 kilometers is around 450 billion Swiss francs. On top of its enormous financial value, our quality of life highly depends on a well functioning utility infrastructure.

In order to plan the underground space, the corresponding spatial information - as in the case of planning on and above the surface - is required. On and above the surface of the earth, capturing such geodata can be solved with today's technical means: in general, the objects to be captured are visible and accessible and the legal framework is already developed. Periodically updated spatial planning and environmental data above ground are available with sufficient quality. The situation is different with the underground. A well defined legal framework and valid standards for data capture and exchange are missing, and the technologies for capturing of existing, buried infrastructure data in subsurface layers are in an early stage of development.

As the national mapping authority, Singapore Land Authority recognises the urgency for a map of the underground and is taking the lead in Singapore. Such a reliable map will avoid uncertainties in planning, design, construction, ownership and maintenance of underground features and developments. In October 2017, Singapore Land Authority, Singapore-ETH Centre, and the Geomatics Department of the City of Zürich started the Digital Underground project with the aim of developing a roadmap towards a reliable map of subsurface utilities.

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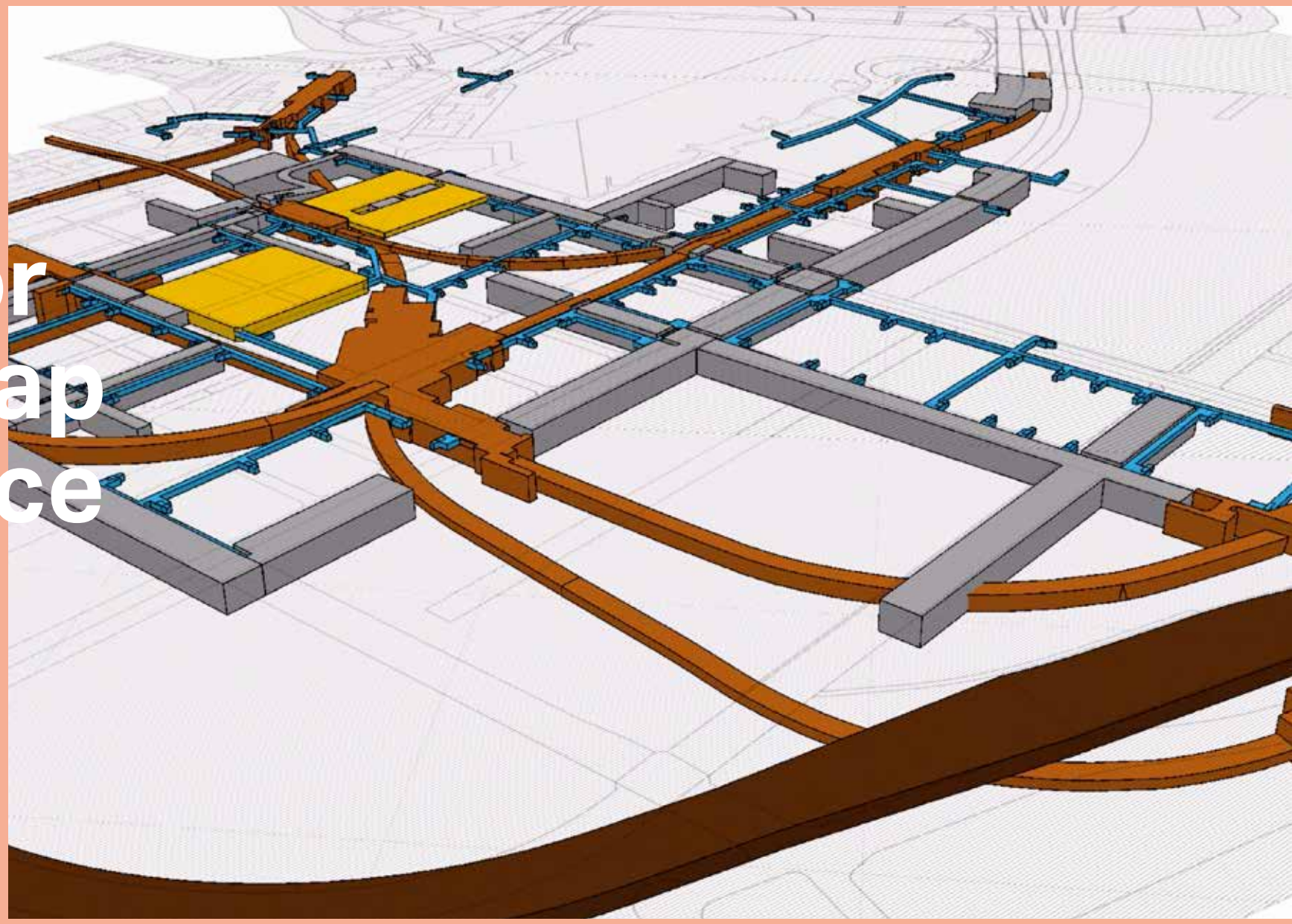
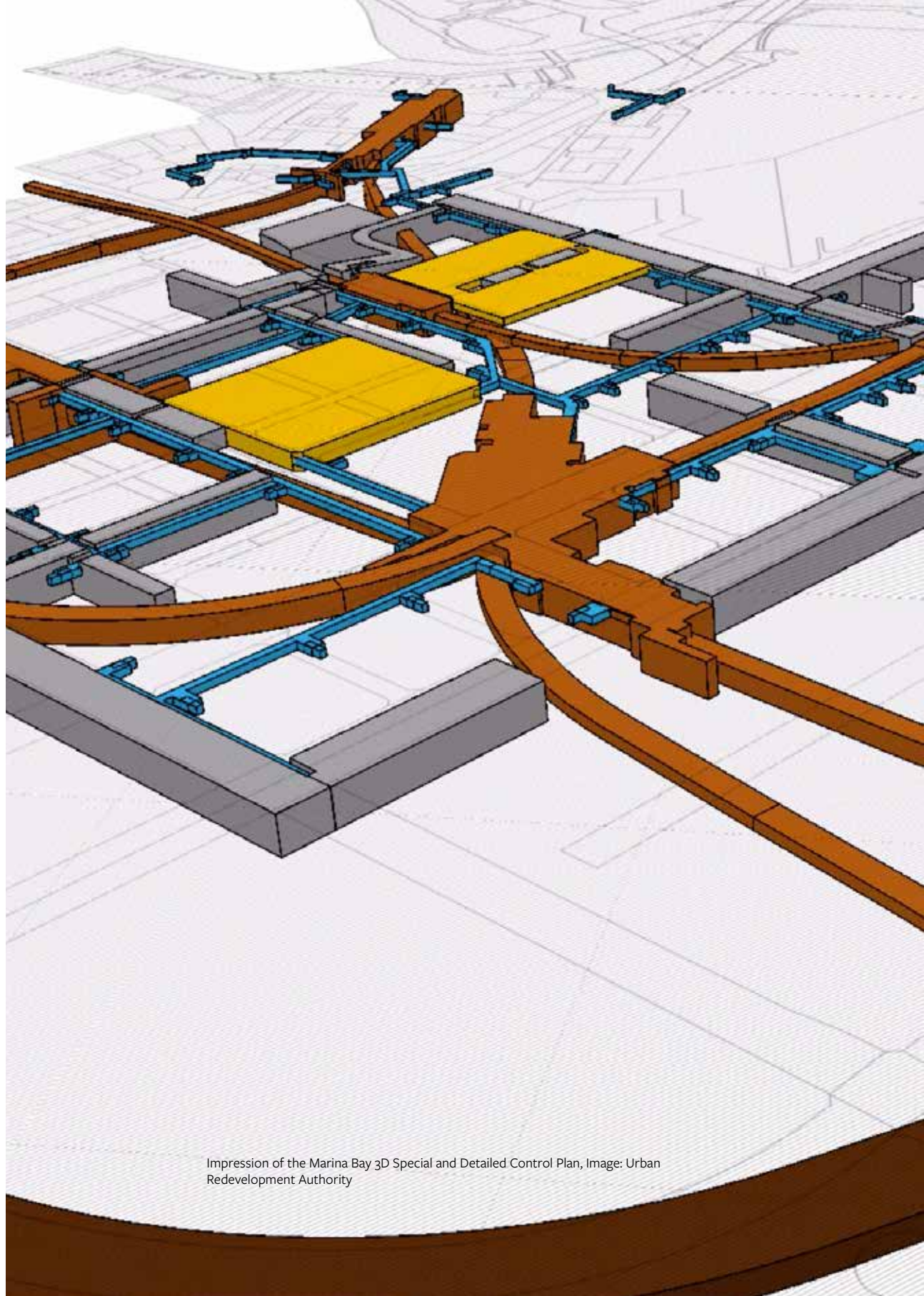


Towards a digital twin of the underground

Imagine the Singapore of tomorrow. A resilient, vibrant city with a high quality of life. A city where land above ground is dedicated to people-centric uses such as housing and recreation. A city where the underground houses things that don't need to be above ground, such as utilities, transportation infrastructure, and industrial storage facilities. A city where heartlands and business districts are connected by an efficient underground transportation system. A city that reliably supplies power, water and other critical services to its residents and businesses.

Singapore is going underground. In March 2019, the Urban Redevelopment Authority of Singapore unveiled its Draft Master Plan 2019 to guide Singapore's development for the next 10 to 15 years. The use of underground space is listed as one of its strategies to create space for the land-scarce city-state's growing needs. A large number of underground developments are already in place, in progress, or planned. As a consequence, Singapore's underground space is becoming more and more congested, and the development and use of underground space is becoming an increasingly challenging task.

To plan, develop, and manage underground space and make informed decisions leading to desirable outcomes, planners, land administrators, and engineers need to make sense of the underground. A reliable digital twin of the underground - a realistic, digital representation of the physical world below the surface - is required. Utilities, consisting of pipes, cables, manholes and other assets that provide electricity, gas, water, wastewater, and telecommunication services, make up a significant portion of the shallow layers of the subsurface.



Impression of the Marina Bay 3D Special and Detailed Control Plan, Image: Urban Redevelopment Authority

The value of a reliable map

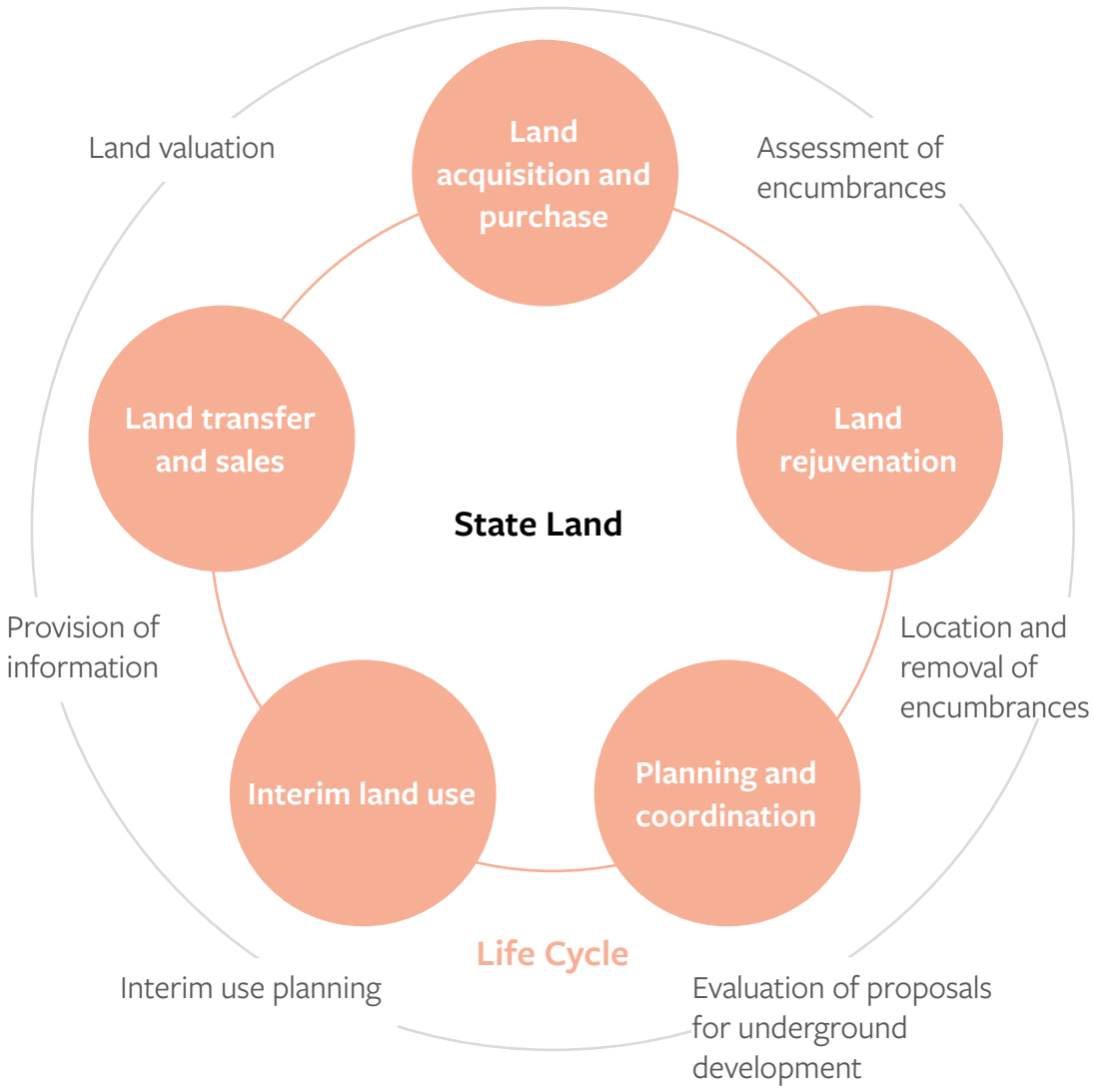
Urban planning
In the best-case scenario, urban planners plan upfront for underground space, in 3D. Reliable information will assist the land development planners of Singapore to plan for future use of underground space, and to maintain the resilience and safety of underground assets by ensuring a minimum clearance. Conversely, the lack of a reliable map may have far-reaching effects, resulting in lengthy and costly planning and development processes, loss of opportunity, and risky and hazardous situations.

Land administration
In Singapore, a large portion of land is owned and actively managed by the state. Reliable information on subsurface utilities has clear benefits all throughout the land's life cycle, resulting in efficient decision-making processes, cost savings, and additional revenues for land administration professionals. Conversely, the lack of a reliable map of subsurface utilities can lead to ill-informed decisions, costly information gathering, and missed business potential.

Additionally, recent changes in land ownership regulations necessitate an accurate record of the alignment of subsurface utilities in order to manage strata titles and officiate any conflicts of underground space. A reliable map of subsurface utilities could eventually pave the way towards the registration of legal space of subsurface utility networks in a cadastre.

Underground construction and excavation works
Before any underground developments such as the laying of new utilities or construction of new MRT stations can commence, existing utilities need to be located in order to avoid any damage and diverting them if necessary. A reliable map is needed to guide the utility location process in order to positively confirm and mark their presence and location. A lack of reliable information may result in considerable delays for the construction process, unexpected locating costs, and utility strikes.

The value of reliable information for planners and land administrators



Tasks and business processes depending on reliable information

Reliability: The product of quality

A reliable map of subsurface utilities can be defined as a map with a sufficient degree of quality to support and benefit urban planners, land administrators, and underground development engineers in their daily work practices. The most important quality characteristics of an underground utility map are (1) accuracy, (2) currency, and (3) completeness.

Accuracy
Spatial data accuracy is the degree of closeness to which data matches the real world. Accuracy is affected by inaccurate measurements, data ambiguity (e.g. values of buried depth relative to a variable reference), data completeness (e.g. by omission of a vertical position), and data veracity (e.g. map features being labelled 'as-built' while being the original design drawing).

Currency
Currency is the degree to which map data is up to date and reflects the current state of the real world. For planning and land administration purposes, besides representing the status quo, underground utility information should incorporate future plans, expected works and diversions, and works in progress.

Completeness
Data completeness is the degree to which all utilities that exist in the real world are represented in the map. A complete map contains all types of subsurface utilities, including abandoned utilities alongside "live" ones.

Digital Underground Project

WP1
Road Map

WP2
Data Capture

WP3
Data Modelling

The Digital Underground project

Singapore Land Authority, the Geomatics Department of the City of Zürich, and the Singapore-ETH Centre are collaborating in the Digital Underground project. The main objective of the project is to develop a roadmap for a reliable digital twin of subsurface utilities. To do so, the project has undertaken a mix of activities aimed at understanding Singapore's current challenges in greater detail and learning about possible solutions.

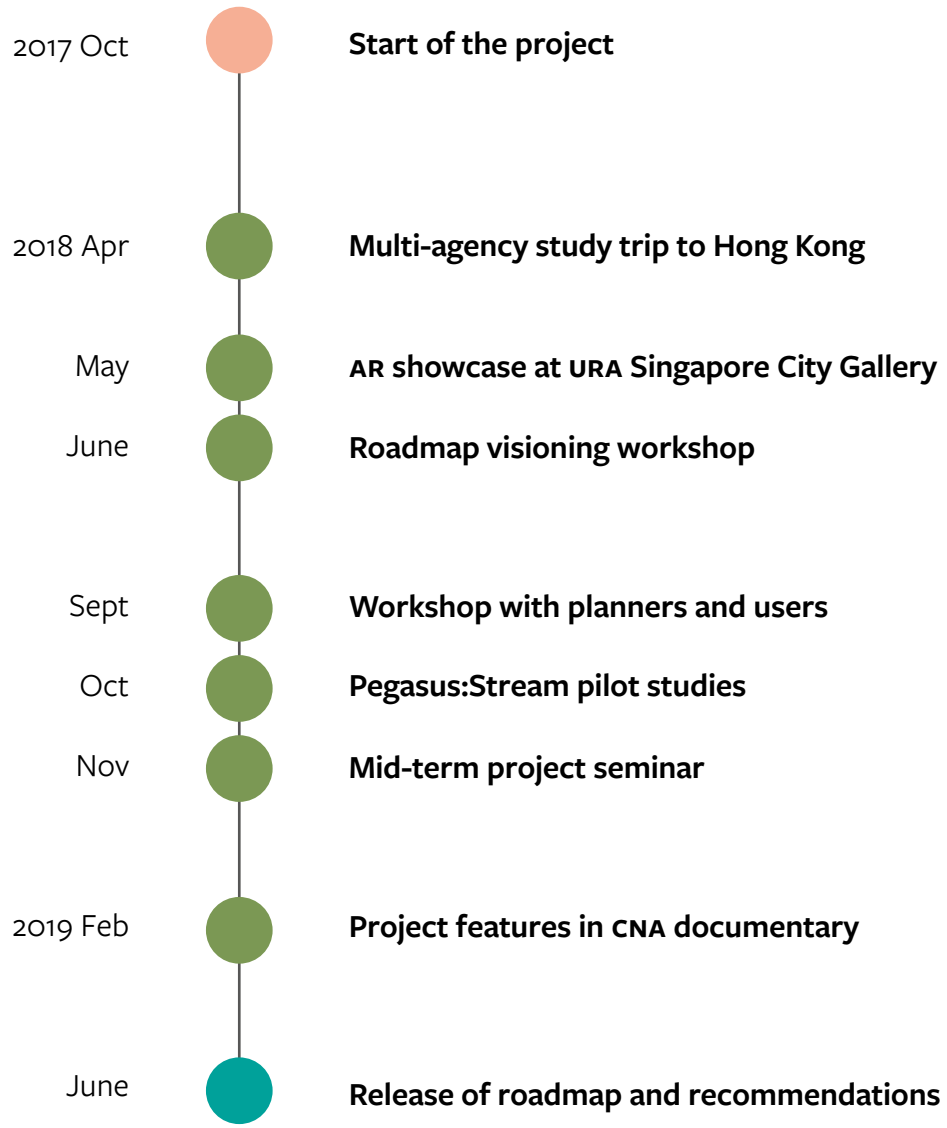
The project consists of three inter-related work packages.

WP1 Roadmap
The objective is to develop the main project deliverable: the roadmap. Through a deep analysis of current practices in Singapore, comparing this to situations in other cities and countries, and a collaborative approach that involves stakeholders from the entire ecosystem, this work package aims to develop a well-supported set of recommendations.

WP2 Data Capture
The second work package focuses on the upstream part of the utility mapping workflow: data capture. Using a combination of desk research and field trials, it will establish a clear picture of the state of the art for data capture techniques and how these techniques can be used to improve the accuracy of captured data, for both newly built and existing buried utilities.

WP3 Data Modelling
The third work package focuses on the downstream part of the utility mapping workflow: modelling and use of the data. The objective is to develop a data model that meets the needs of end users and to investigate how captured data can be modelled into the desired format. This data model serves as a blueprint for the development and implementation of a consolidated map of underground utilities.

Project highlights



Work package 1: Roadmap

The development of the roadmap is supported by three main activities:
- Analysis of the situation in Singapore
- Analysis of utility mapping ecosystems overseas
- Collaborative roadmap development

Assessing the state of quality in Singapore
In order to understand specific challenges in Singapore better, Digital Underground engaged various key players in the utility mapping process. Over the course of the project, representatives from land development agencies, utility agencies, contractors and surveyors were interviewed on what they view to be the biggest challenges on the path towards a reliable map of subsurface utilities.

Looking overseas
Subsurface utility data quality is a topic that is globally relevant. The team has sought out other cities to study their efforts and practices. The following cities were studied:
- The Hong Kong Special Administrative Region
- The City of Zürich
- The Municipality of Rotterdam

Engaging stakeholders: Foundations for an ecosystem
A roadmap needs the support of its stakeholders that are required to put its recommendations into practice. The team has reached out to government agency representatives to share their insights, inputs and feedback on the roadmap. The first event was the Underground Café workshop on the closing day of the Hong Kong study trip. After that, the team followed up with collaborative workshops.

↑ Digital Underground Hong Kong study visit, April 2018. Image: Rob van Son
↓ Digital Underground visioning workshop, June 2018. Image: Rob van Son

Looking overseas: Hong Kong

Key takeaways:

- *Dense urban area with challenges similar to Singapore*
- *A well-established infrastructure for capacity development, from education directly to industry*
- *Presence of an extensive research facility that facilitates education, research and innovation*

The Department of Land Surveying and Geo-informatics of Hong Kong PolyU has provided bachelor-level education since 2009, providing skilled utility surveying graduates to the professional sector. The education programme shows that underground surveying and mapping is recognised as a multi-disciplinary and non-traditional profession, integrating not only land surveying and GIS but also near-surface geophysics, civil engineering, signal processing, and even human psychology.

The underground utility survey lab is a core enabler of utility education in Hong Kong. It contains scaled-down utility networks and a matrix consisting of metallic and non-metallic fresh and salt water supply pipes, drainage and sewerage pipes connected to manholes, power and gas cables, and valve chambers of various kinds comparable to actual field conditions. It is designed to match the complicated and congested subsurface utilities of Hong Kong. It provides an indoor and controllable environment where orientations, depths, sizes, material types, coordinates of various utilities networks can be carefully designed and recorded.

In the lab, students and practitioners can operate various survey instruments to survey and map the underground utilities and other objects, allowing them to build confidence for future field work and validate non-destructive testing and survey methods and procedures, including the positioning and mapping of the utilities affected by buried depths, sizes, and material types.

↑ The Utility Surveying Lab at Hong Kong PolyU. Image: Hong Kong PolyU
↓ The Utility Surveying Lab at Hong Kong PolyU. Image: Hong Kong PolyU

Looking overseas: City of Zürich

Key takeaways:

- *Trusted and reliable surveying of utilities by utility operators*
- *A well defined framework for coordination, governance and legal aspects of data capture and data delivery*
- *A long history of sharing data has led to trust, eventually leading to public access to all underground utility information*

The City of Zürich has its own utility cadastre since 1999 and set up a governance framework with the corresponding utility providers. The most important types of utilities are included: gas, water, sewage, district heating, power, and telecommunications.

The data is automatically delivered through well defined interfaces at least once a week by the utility owners to the cadastre operator (GeoZ). GeoZ then serves a consolidated database containing complete, regular, and unchanged information to users through a public web portal, free of charge. The positional accuracy of the utilities is in the range of 200 millimetres and known inaccurate utility information is marked accordingly.

In the near future, the City of Zürich intends to move to a 3D map of subsurface utilities, with 3D surveying already ongoing at the moment. Additionally, the cadastre will include additional utilities such as public transport and traffic control related assets, and data will be provided in a BIM format.

↑ Digital map of subsurface utilities in Zürich. Image: City of Zürich
↓ Integrated above and below ground 3D digital twin. Image: City of Zürich

Looking overseas: Rotterdam

Key takeaways:

- *Supervision of the utility laying process ensures accurate data capture*
- *The plan permit is effectively used by the Utility Bureau to establish leverage over the utility laying process*
- *Years of collaboration lead to trust and solid working relationships between municipality, utility owners, contractors, and surveyors*
- *Surveyors are able to work independently, and report directly to the municipality*

Driven by a need to ensure availability of underground space for future use and to provide a safe and resilient utility infrastructure to both the city and the economically vital port area, the Municipality of Rotterdam established the Utility Bureau.

Through the Utility Bureau, the municipality assumes a pro-active, coordinating role for the planning, development, and mapping of subsurface utilities. The core tasks of the Utility Bureau are (i) the approval of all utility laying plans in the municipality, (ii) accurate surveying of the location of utilities, and (iii) supervision of utility laying and surveying processes.

The Utility Bureau assures the accuracy of information through supervision and coordination of the utility laying process, ensuring that a qualified surveyor is provided with the right opportunity to capture the necessary data. Through this mechanism, reliable data is collected directly by the municipality, made available for planning and land administration purposes, and shared to the public. Years of working in this structure have led to a strong understanding and working relationship and trust between municipality, utility owners, contractors, and surveyors.

Work package 2: Data capture

There are many techniques available for mapping subsurface utilities. Each technique has its own specific use cases, benefits, and limitations. How can these techniques be employed to assure the accuracy of information on newly built utilities and improve the accuracy of information on existing subsurface utilities? Digital Underground assessed a few techniques in detail, and highlighted others in showcases and demonstrations throughout the project.

Conventional surveying
Conventional surveying using a total station or GNSS RTK is the standard technique for data capture of newly built utilities.

Laser and photogrammetry
Laser scanning offers rapid and highly detailed 3D data capture for open trench situations.

Ground penetrating radar
GPR is a non-destructive geophysical technique that can be used to "see" the unseen below the surface.

Gyroscopic mapping
Pipes that are installed using a trenchless technique, can be mapped by pulling a device through them.

RFID markers
Remotely detectable tags on utility assets can continuously provide location information without the need to expose them.

↑ Total station surveying in progress at Cecil St, March 2019. Image: Rob van Son
-- Laser scanning in progress at Yishun Ave 6, March 2019. Image: Rob van Son
↓ RFID detection in progress at Serangoon Garden Way, March 2019. Image: Rob van Son

Seeing the unseen with ground penetrating radar

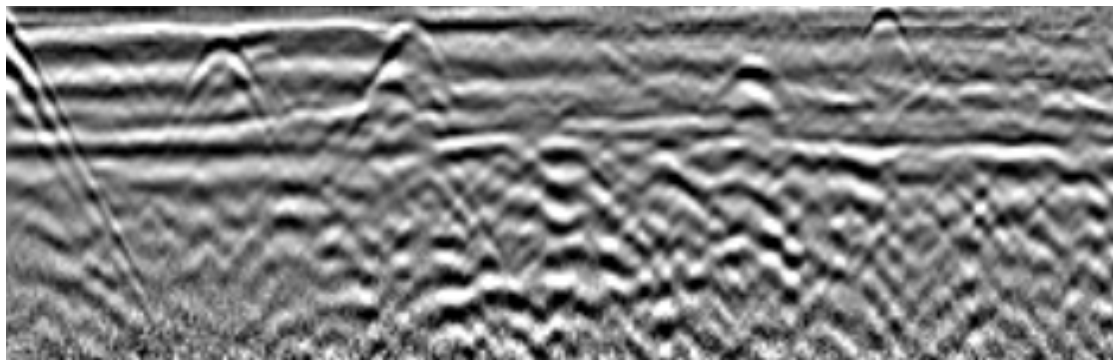
The best opportunity for mapping a utility is undoubtedly when it is exposed, visible, and accessible. For existing utilities buried below the surface, this opportunity may never arise again. Non-destructive geophysical techniques such as ground penetrating radar (GPR) can be used to detect and locate subsurface utilities. Field trials were conducted to assess GPR as a technique for mapping existing utilities in Singapore.

Field trials in Singapore

To assess the accuracy, scanning depth, and general effectiveness of GPR as a mapping technique in Singapore, field trials were conducted. Each trial consisted of a direct, open pit measurement followed by GPR measurements after backfilling. To identify and leverage on these opportunities, Digital Underground collaborated with Futurus Construction.

Invaluable experts

GPR data capture produces radargrams as its primary data. These images are not as easy to interpret as photos. The presence of a hyperbola indicates the potential presence of an object buried underground, and many hyperbolas near one another in a linear pattern could indicate the presence of a pipe or cable. A skilled and seasoned expert is required to analyse and interpret the data in order to detect subsurface utilities.



↑ B-scan radargram with hyperbolas incdicating possible utilities. Image: Jaw Siow Wei
→ GPR scan in progress at Cecil St, April 2019. Image: Rob van Son

Mobile mapping using 3D ground penetrating radar

Ground penetrating radar (GPR) is a feasible technique for detecting underground utilities. However, data capture and processing is laborious, even for relatively small areas. How does this technique translates to the application of mapping existing utilities in order to improve information accuracy? High-end 3D GPR arrays offer the potential of high-resolution data capture at an unprecedented speed and volume.

An ASEAN first
Digital Underground collaborated with Leica Geosystems and IDS Georadar to bring the Pegasus:Stream into Singapore. It was its first appearance in Southeast Asia.

Leica Pegasus:Stream
The Leica Pegasus:Stream towable mapping platform consists of a Leica Pegasus photo and laser scanner and an IDS Georadar Stream EM ground penetrating radar array. The array consists of 40 antennas in two polarizations, operating at different frequencies. This enables the system to capture all necessary data for a wide surface in a single pass.

Heartlands to CBD
Over the course of 6 days, the team captured data from a representative mix of areas in Singapore: from old residential estates such as Ang Mo Kio and Toa Payoh to newer ones such as Punggol and Sengkang, and areas around Marina Bay.

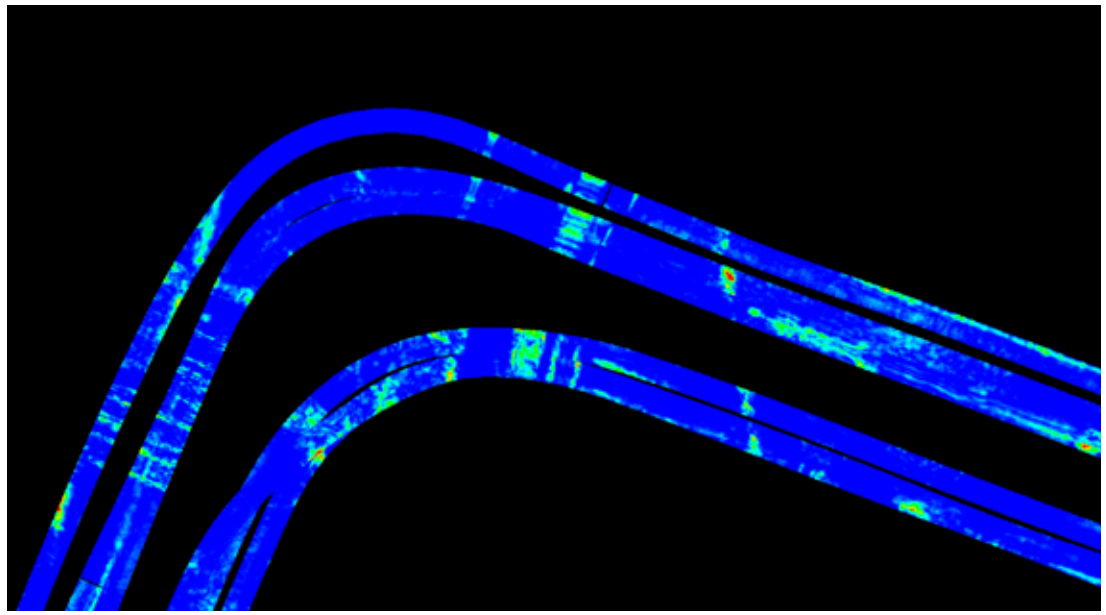
The team's work with the Pegasus:Stream platform was featured in Channel NewsAsia's documentary Land Unlimited, Episode 1: Underground Dreams.

↑ Leica Pegasus:Stream in Ang Mo Kio. Image: Leica Geosystems Singapore
↓ Deployment of Leica Pegasus:Stream in Toa Payoh. Image: Leica Geosystems Singapore

Mapping Toa Payoh

Toa Payoh is an old residential estate in Singapore, with developments dating back to the late 1960s. For Digital Underground, this makes it an interesting and challenging case study area. Utilities have gradually been constructed, renewed, and replaced underground over the course of many decades, mostly in uncoordinated fashion. Digital records of underground utilities have only become available in more recent times, raising questions on the accuracy of information of existing subsurface utilities.

On Friday 26 October 2018, the Pegasus:Stream mobile mapping platform was deployed to capture data along a 1.8 kilometre bi-directional four-lane road north of Toa Payoh MRT. The data was captured at a speed of 15 kilometres per hour. As operation took place in regular traffic conditions, a motorcycle escort guided the towing vehicle and the platform to ensure a safe situation for everyone involved. Scanning of the entire area took approximately three hours. Over the course of the following three weeks, the captured data was processed using specialised software and a total of 109 (hypothesised) subsurface pipes and ducts were detected in the area.



↑ Scanning in progress in Toa Payoh, October 2018. Image: Rob van Son
↓ GPR scan tracks in Toa Payoh. Image: Jaw Siow Wei

Work package 3: Data Modelling

Data modelling is an essential part of the utility mapping workflow that includes data capture, data processing, data integration, data storage and application. A subsurface utility data model is a conceptual model that describes the structure and content of geodata independent from the used hard- and software systems. It will provide the standard for the presentation of geometrical information, data quality management and various applications.

A pilot study was designed to test the workflow from data capture to application. It is essential to ensure that the data needs of end users are met and a consolidated map of subsurface utilities is established and maintained. Captured data may come from different sources, such as different surveying techniques, a design drawing, or even an existing map. This means that data modelling needs to deal with data of different types, formats, resolution, degrees of accuracy, reliability, and completeness. This data may come in at different stages of a utility's life cycle, with long periods inbetween.

Real world to GIS applications

Data capture in the real world

Model

Consolidated 3D Database

Enable

3D GIS applications

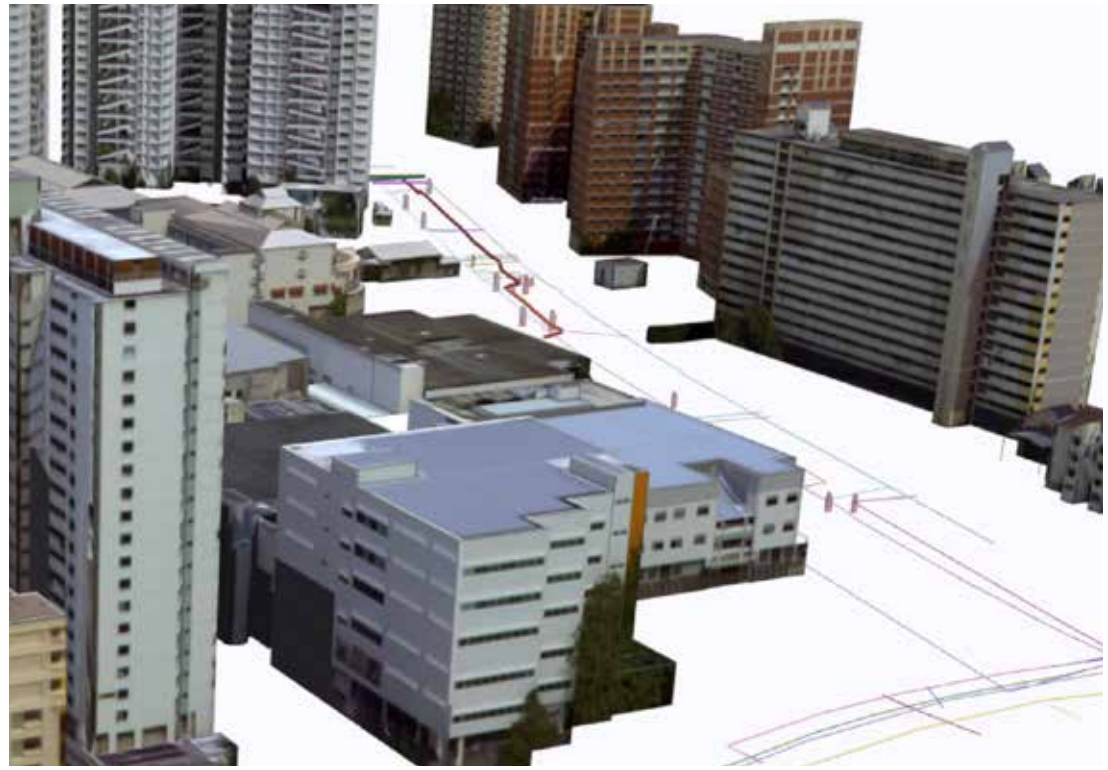
- Urban planning
- Evaluation of underground plans
- Land administration
- Management of underground land ownership

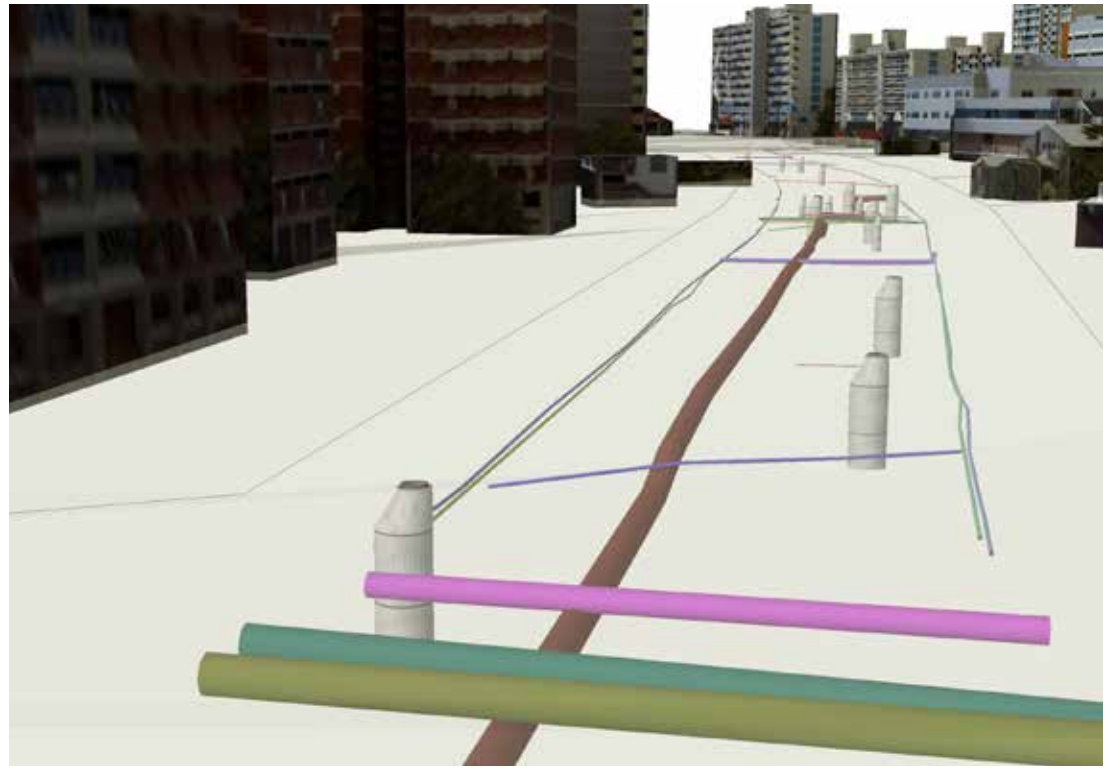
A data model for subsurface utilities land administration

Based on the results of a workshop with land administration professionals of the Singapore Land Authority, a conceptual data model for subsurface utilities land administration was developed. The data model consists of three main components:

- Utility, a 3D representation of subsurface utility assets:
- Survey, containing information about the survey source, and the quality and reliability of the data.
- LADM, linking subsurface utilities to existing cadastral maps.

Following the case studies conducted with the Pegasus:Stream mobile ground penetrating radar platform, Digital Underground explored how the data could be modelled from available map data and the subsurface utilities that were detected and extracted in Toa Payoh. The modelling process consisted of (i) identifying detected features using available GeoSpace data, (ii) 3D modelling of the identified features, and (iii) fusion with Singapore's cadastral maps. Although not all detected features could be positively identified, those that could were modelled in 3D with cadastral lots associated with them. The results were eventually showcased in a demonstrator application highlighting the value of reliable 3D information subsurface utilities for land administration purposes.





↑ 3D utility features in Toa Payoh integrated with building models, Image: Yan Jingya
↓ Up close view of 3D utility features in Toa Payoh, Image: Yan Jingya

Next Steps


Suggested workflow
Individual brainstorm on small post-its for sub-question #1
Gather everything on flipchart; discuss in group
Group/cluster inputs. Use large post-its to describe groups
As a group, use small post-its to generate input for sub-questions #2 and #3. Put on flipchart
EXIT

Vision for a thriving ecosystem

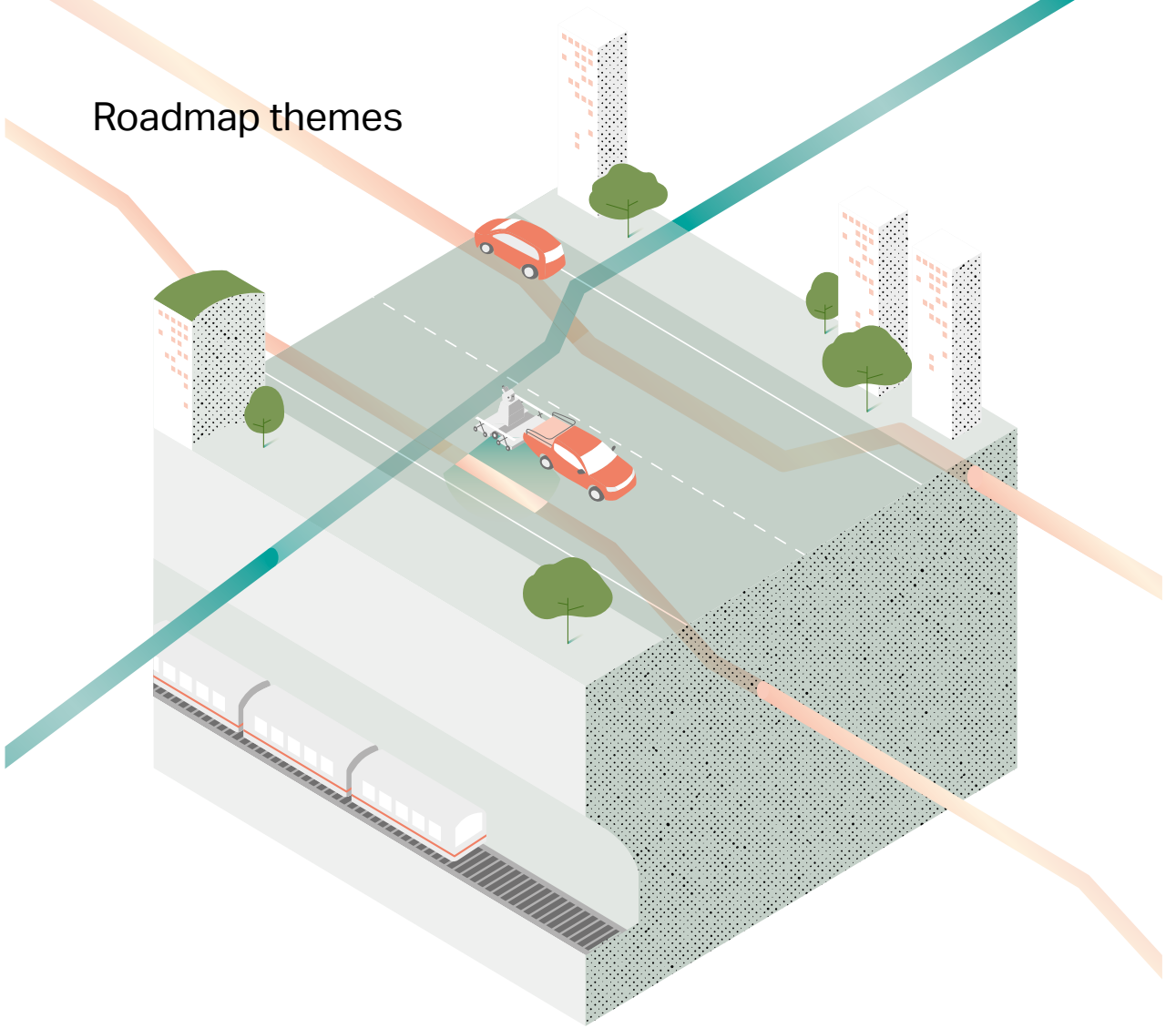
The delivered roadmap will establish a reliable map of subsurface utilities in Singapore. The vision describes that final product and the actors that enable and benefit from it:

A reliable map of subsurface utilities will contribute to a smart, resilient, and sustainable Singapore and will enable professionals to make informed decisions.

Planners, land administrators and underground development engineers have access to accurate, up to date, and complete information of subsurface utilities which directly benefit their work processes.

Surveyors and mappers have the capacity to produce reliable and accurate 3D information of subsurface utilities.

Soon after Digital Underground had commenced, it became clear that this vision shall only be realised through an integral, "whole ecosystem" approach. Therefore, the roadmap makes recommendations that do not only cover technology, but also governance, legislation, capacity building, collaboration, research, and development. The roadmap is organised along 5 themes, grouping together similar and inter-related activities: Coordination, consolidation, capture, capacity, and community.



Coordination
Coordination of a national mapping strategy

Consolidation
Consolidation of subsurface utility information in a national map

Capacity
Develop the required capacity

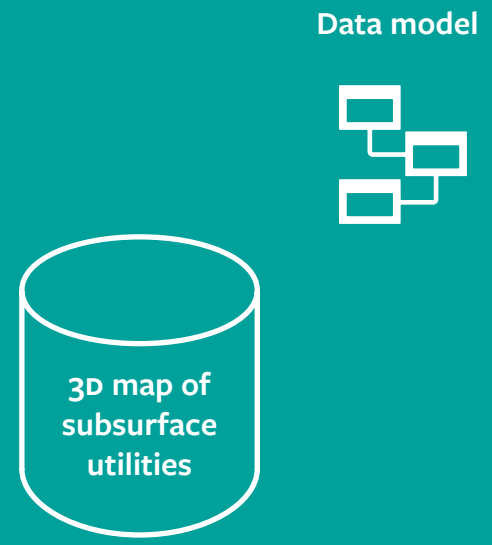
Capture
Reliable data capture for newly built and existing, buried utilities

Community
Engage a community of practice from industry, government and academia

After Digital Underground: Recommended next steps

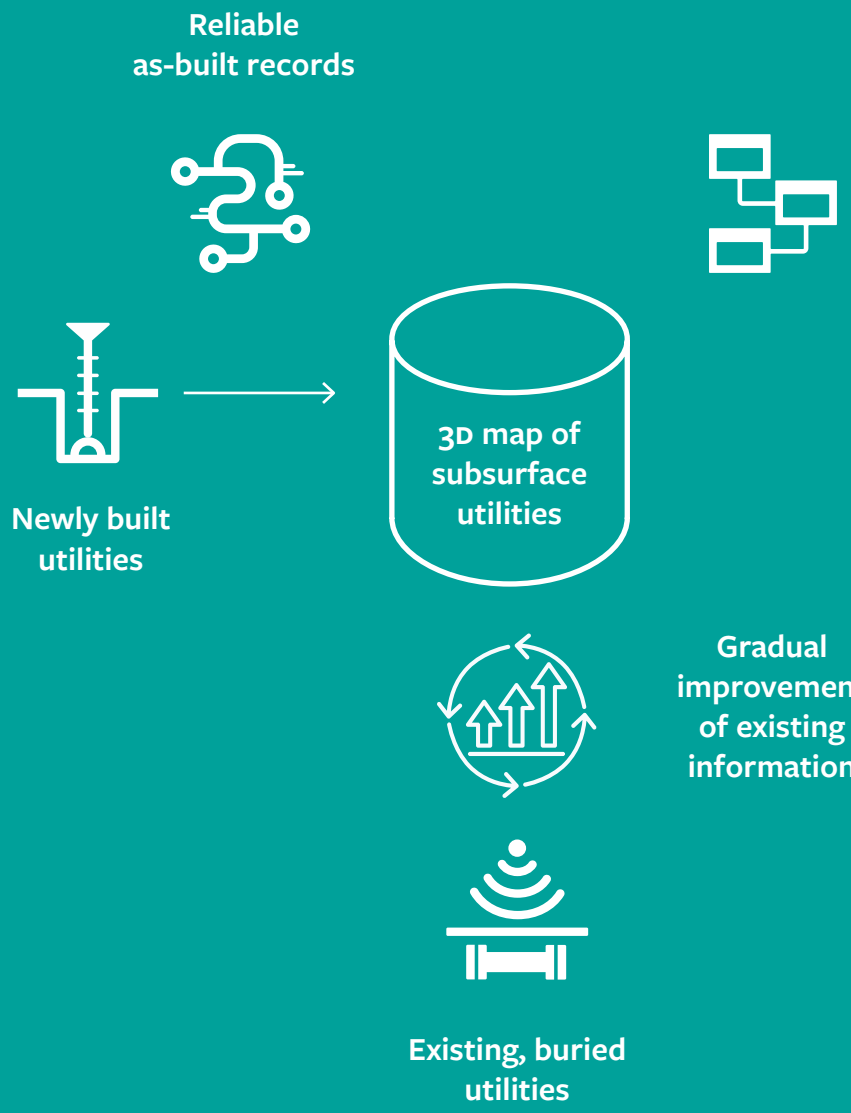
1 Establish a national map of subsurface utilities

- All utility information in one database, fully 3D
- A data management infrastructure that includes data submission, quality control, modelling, and delivery
- Defined and classified accuracy and quality
- Implementation based on the data model developed by Digital Underground



2 A national mapping strategy for subsurface utilities

- Ensure accurate data capture for newly built utilities
- Capitalize on large underground infrastructure projects to reconcile accuracy of information on existing utilities
- Capitalize on other mapping opportunities that occur throughout the life cycle of utility assets (e.g. repair, rehabilitation) to reconcile accuracy of information on existing utilities
- Enabled by policies, processes, people, and technology



A reliable map of subsurface utilities will contribute to a smart, resilient, and sustainable Singapore.

↑ Digital Underground Hong Kong study visit, April 2018. Image: Wong Kia Fu
↓ Digital Underground Hong Kong study visit, April 2018. Image: Digital Underground

↑ Digital Underground Hong Kong study visit, April 2018. Image: Digital Underground
↓ Utility Survey Lab at Hong Kong Polytechnic University. Image: Hong Kong PolyU

↑ Leica Pegasus 2 in Marina Bay, October 2018. Image: Leica Geosystems Singapore
↓ Leica Pegasus:Stream in Marina Bay, October 2018. Image: Leica Geosystems Singapore

↑ Leica Pegasus:Stream in Marina Bay, October 2018. Image: Leica Geosystems Singapore
↓ Close-up view of IDS Georadar Stream EM GPR array, October 2018. Image: Rob van Son

↑ Field work in NUS University Town, September 2018. Image: Rob van Son
↓ Digital Underground showcase at URA Singapore City Gallery, May 2018. Image: Yan Jingya

↑ Field work in NUS University Town, September 2018. Image: Rob van Son
↓ Documentary filming in progress, November 2018. Image: Rob van Son

Closing

Prof Dr Gerhard Schmitt

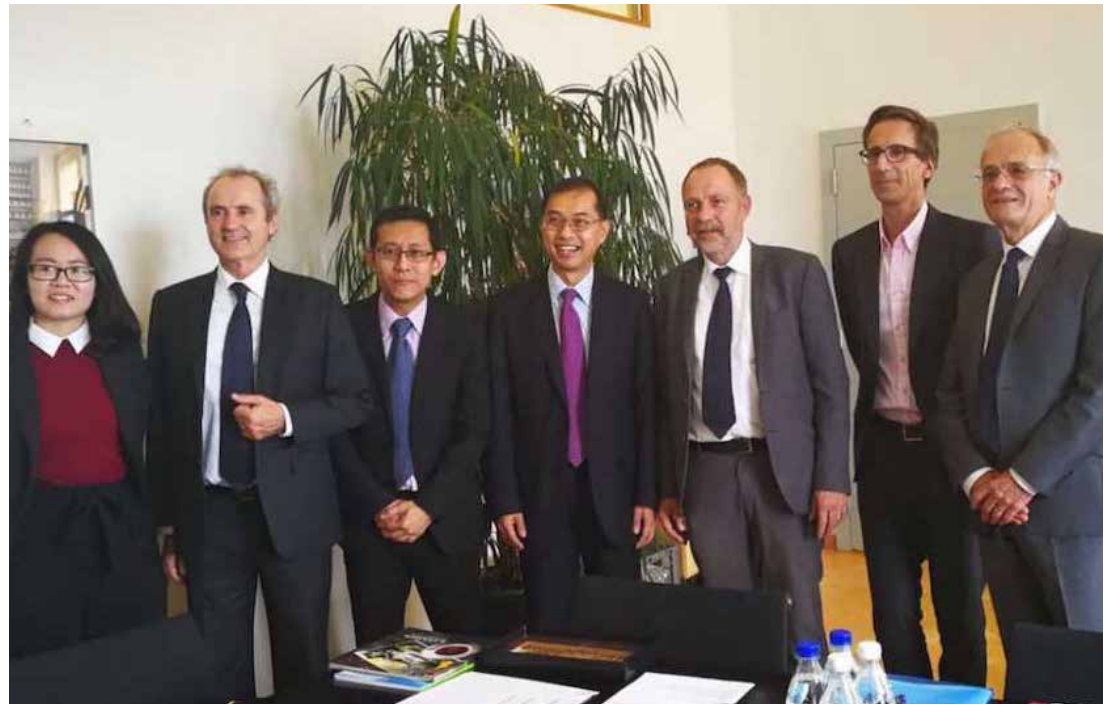
The Digital Underground project was initiated by the Future Cities Laboratory (FCL), one of the two research programmes at the Singapore-ETH Centre. The centre aims to strengthen the capacity of Singapore and Switzerland to research, understand and actively respond to the challenges of global environmental sustainability.

The first phase of the Future Cities Laboratory (2010-2015) produced a rich legacy of research, which represents an important part of the FCL programme in its second phase. It also demonstrates our commitment to train, mentor, and support professionals to develop skills and know-how to translate advanced research to practice. At the moment, there are 10 ongoing "research-to-application" projects. One of them is Digital Underground.

In October 2017, the Singapore Land Authority, Singapore-ETH Centre, and the Geomatics Department of the City of Zürich started the Digital Underground project. It was officiated with the signing of a research collaboration agreement between the Singapore ETH-Centre and the Singapore Land Authority at ETH Zürich in Switzerland.

In the Digital Underground project, the cities of Singapore and Zürich have benefited from the close collaboration. Singapore is learning from the experiences in Zürich in setting up a consolidated database. Embedded in a well described governance and legal framework, it allows geodata to be managed and maintained to the highest quality. Zürich is benefiting from research results of new surveying technologies to capture 3D data of existing underground utilities, in order to cope with complex subsurface conditions for future city development.

Digital Underground has shown how little we know of what exists below the surface. We need a digital twin of the underground that will cover many dimensions from infrastructure to thermal qualities and water resources, making the underground a crucial partner for the future sustainable and responsive city. This project is therefore just the beginning of a long-term development.



↑ Signing of the research collaboration agreement between the Singapore Land Authority and Singapore-ETH Centre, October 2017

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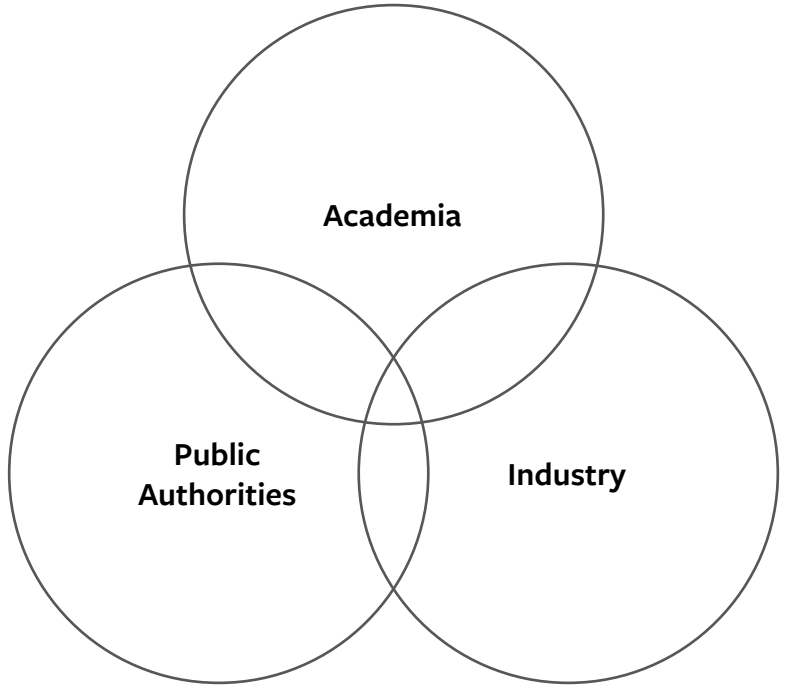

- Singapore Land Authority
- Stadt Zürich

- Leica Geosystems
- IDS GeoRadar
- Futurus Construction

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