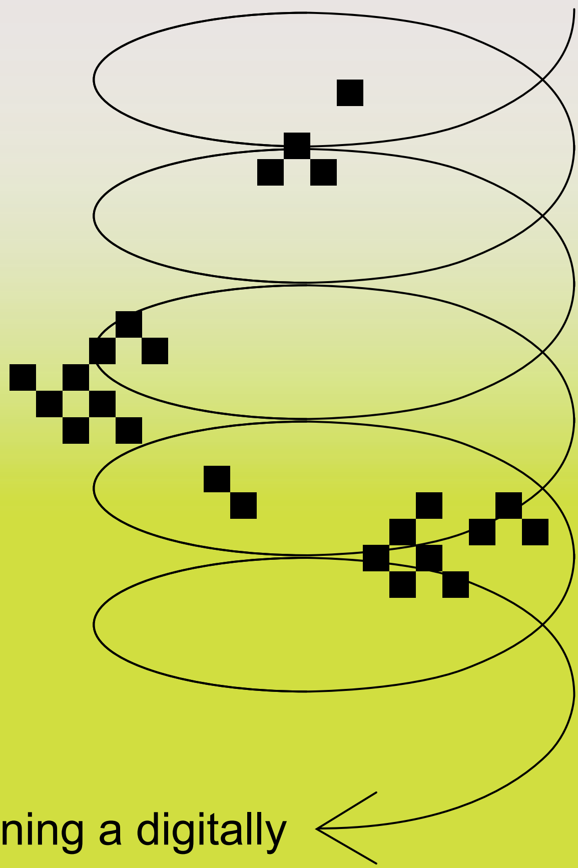
(SEC) SINGAPORE-ETH
CENTRE

DIGITAL
UNDERGROUND

Digital Underground



Phase 2

Imagining a digitally
enabled future

Content

Digital Underground — The new frontier

The earth's underground and its digital twins are surprisingly little known and explored territories with tremendous potential.The long-term challenge is to develop technologies for a complete more-dimensional and holistic real-time mapping of everything below the surface: objects, functions and behaviours. This requires the collaboration between sciences and disciplines such as geology, environmental science, architecture, archaeology, engineering, computer science, city agencies and industry. The Digital Underground project, supported by specialists in Singapore and Zürich, is a pioneering and promising step in this direction.

Cities and settlements scratch and puncture the physical underground and use it for their infrastructure. Digital twins of the physical urban underground help to acquire a holistic understanding of the interaction with the world we build on. They open up vast possibilities for a more efficient and mindful dealing with the underground in the future. Probably few cities have physically changed the original ground they were founded on as much as Singapore. Since the early years of the republic, millions of tons of material were moved from the surface of the island into the sea for land reclamation. Extensive tunnels for purposes from transportation to storage produced much needed additional material and changed the structure of the underground at the same time.

Digital twins of cities are the basis for performing simulations of urban futures. Most digital twins represent parts of the functions and behaviours of physical structures on and above ground. Above ground, visualisations of simulations are easy to compare with built reality as they are directly visible to the human eye. Below ground, visibility of embedded infrastructure is zero for the naked eye, and new ways of mapping and visualisation are needed to make the invisible visible.

Imagine we could completely visualise everything that is static and dynamic in the underground: building foundations and infrastructure, archeologically interesting ruins, environmental threats from landfills, flows of water, temperature and humidity conditions. It would make urban planning, transportation, circular use of resources and intelligent application of materials much more efficient and safe. It would avoid huge costs from repairing unnecessary damages and unlock a gigantic potential for energy savings. Digital Underground connects the cities of Singapore and Zürich. Never before, two cities, agencies, universities and industry within the city have worked together that closely in research and development to benefit their people and to avoid unnecessary destruction of values while maintaining and improving the underground network of infrastructure. Enjoy reading the exciting steps towards this goal!

Zürich, August 2021

Prof. em.
Dr. Gerhard Schmitt
Principal Investigator of
Digital Underground

Gerhard Schmitt is professor emeritus for Information Architecture at ETH Zürich. His research interests include the development of Artificial Intelligence supported design systems in Architecture, the implementation of large scale Virtual Reality systems, digital urban twins to simulate the Urban Heat Island effect and designing planning actions to reduce it. He was the Principal Investigator of the Digital Underground project.

Preface

The case for a reliable digital twin

Reliable information on subsurface utilities is essential for Singapore to fulfil its ambition of utilising underground space to optimise land use and improve liveability above the surface.

The availability of a digital twin benefits planners, land administrators, and many other stakeholders involved in the development of underground space and infrastructure.

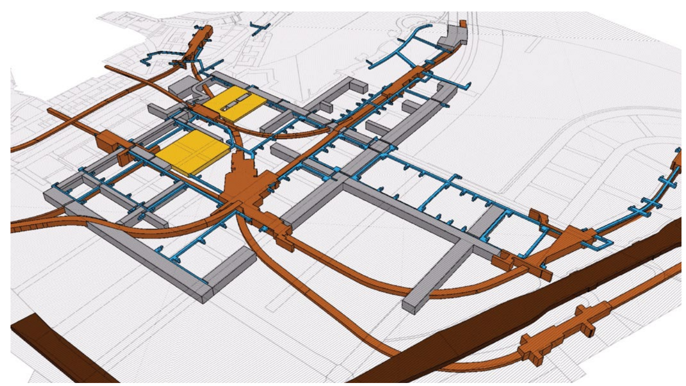
The underground: Opportunity or obstacle?

Singapore is going underground. Reliable information on the presence and location of subsurface utilities can make a critical difference for the city-state to realise its ambitions.

While the challenge of land scarcity is almost as old as modern Singapore itself, only in recent years, the use and development of underground space has become a prominent strategy for optimising land use by placing facilities and infrastructures underground and freeing up land above the surface for more liveable uses. In order to “go underground” and effectively plan, develop, and use the space, it is necessary to look at space in a different way from before. While previously it may have been sufficient to treat space as a flat or two-dimensional surface, going underground means incorporating the vertical dimension and treating space as a three-dimensional volume.

Going underground not only requires a new perspective. It requires an understanding of what exists below the surface and where. In densely populated urban areas such as Singapore, many structures and other encumbrances already exist underground. Not knowing what is there and where things are can make the planning, design, and construction of new infrastructure a challenging, risky, and costly effort. This is particularly relevant for utility networks which, for most of their lifetimes, are surrounded by soil and hidden from plain sight. Hence, professionals rely on maps, plans, models, and drawings for guidance and information. Since long ago and up until now, authorities and companies have been mapping the location of underground utilities. Advancing from paper and hand drawn maps in the past to, more recently, digital maps and drawings that capture locations in the horizontal plane. We are now witnessing a move towards three-dimensional maps that can be used for digital planning, design, and coordination of developments.

However, much of the available information is unreliable. It may be inaccurate, incomplete, or outdated, or its quality simply unknown, establishing a conflict: On one hand, the underground presents a tantalising opportunity for cities aiming to optimise the use of space. On the other hand, due to a lack of reliable information, the underground and the structures within can become a figurative and literal obstacle towards realising cities’ ambitions for the future. The Digital Underground project aims to contribute to the realisation of those aspirations by working towards a reliable digital twin of subsurface utilities.



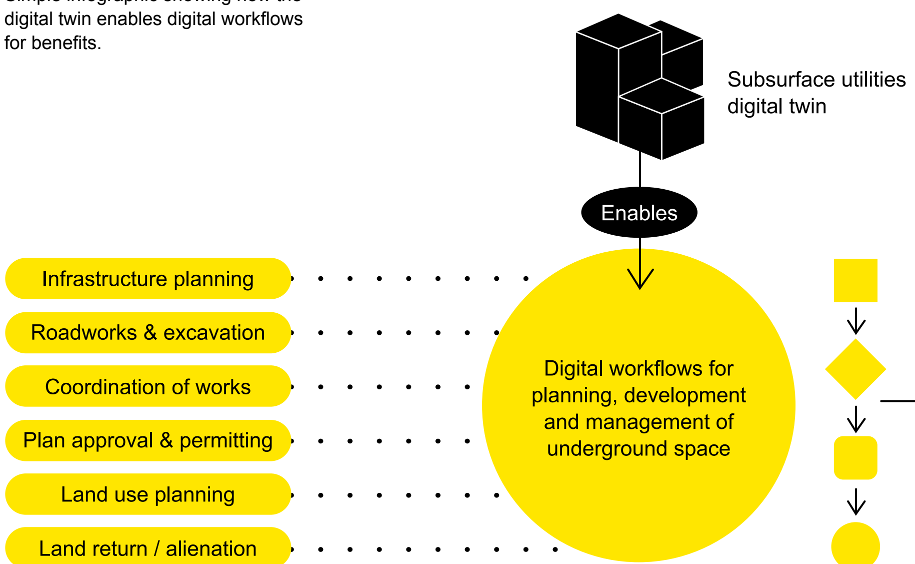
The Marina Bay Special and Detailed Control Plan defining current and future planned use of underground space, setting the stage for a three-dimensional approach to underground urban planning.

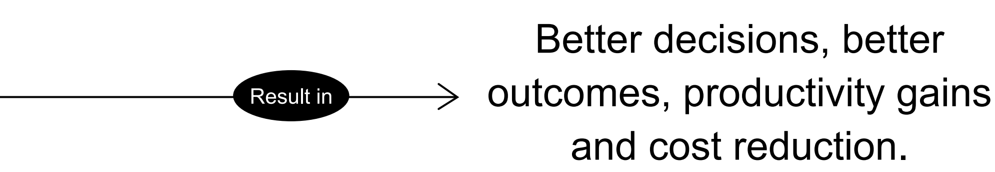
Image: Urban Redevelopment Authority

Benefits of a national subsurface utilities digital twin

A lack of reliable information on subsurface utilities affects Singapore and its ambition to “go underground”. What benefits and added value can be expected from the availability of reliable information and how does this justify our efforts to improve the quality of available information?

Simple infographic showing how the digital twin enables digital workflows for benefits.





The lack of accurate, current, and complete information on subsurface utilities is affecting professionals and business processes in the public and private sector daily, from the planning of new towns and infrastructure to the execution of construction works to the management of land and infrastructure assets. Unreliable information on subsurface utilities increases risk and uncertainty, leading to long lead times and delays, increased expenditure, and lost opportunities to capitalise on already scarce underground space.

Nowhere are the consequences of unreliable information more visible than in the open public space. Repeated and extensive efforts are undertaken to improve stakeholders’ information position on subsurface conditions, evidenced by the countless trial holes excavated on Singapore’s roads to verify the presence and location of existing structures. Professionals working on site are exposed to safety hazards due to the risk of utility strikes during excavation. And disruptions of services resulting from such excavation damages or other causes affect the countless residents and businesses relying on performant and reliable services. Singapore, as a Smart Nation, increasingly relies on digital information. For Digital Underground, the digital twin is a dynamic, digital representation of all physical subsurface utility assets in Singapore that enables well-informed digital workflows and applications that lead to better decisions and efficiency gains:

Better decisions and outcomes — Better planning, design, and implementation of land and infrastructure assets, resulting in a more efficient use of space and preservation of opportunities for future use.

Cost reduction and productivity improvement — Improved turnaround time, a reduction of verification activities on the ground, and an overall improvement of productivity for utility agencies, planners, engineers, and other professionals inthe public and private sector for planning, constructing, and managing land and infrastructure assets.

Resilience and safety — A more resilient and performant infrastructure with less downtime and interruptions and safe working conditions for professionals in the construction industry.

From planning to construction: Use cases of a subsurface utilities digital twin

Michelle Chan Mei Har
Singapore-ETH Centre

Understanding how users benefit is essential for the justification and guidance of the development and improvement of a subsurface utilities digital twin.

The case for a reliable digital twin

Potential data beneficiaries were engaged to document their information needs, experiences in using available data, and the expected benefits and value gained from having access to a sufficiently accurate, up to date, and complete source of information on subsurface utilities. The findings show that many professionals from various public and private sector organisations will benefit from reliable information on the state of the underground — which includes but is not limited to subsurface utilities — throughout their efforts in developing and managing Singapore's underground space and infrastructure. However, critical data quality and availability challenges need to be overcome to achieve the expected productivity gains, reductions of development cost, risks, and uncertainty, and a better allocation of underground space to accommodate Singapore's ever growing and changing needs.

Beneficiaries of information on subsurface utilities are predominantly professionals and specialists that are in the business of developing and managing underground infrastructure in Singapore. They range from legislative controllers, urban planners, infrastructure designers, contractors, and surveyors from both public and private sector organisations. The Digital Underground team conducted surveys and interviews with these (current and future) users to get a detailed understanding of their needs, expected benefits, challenges, and aspirations for a future (digital) underground.

From the studies, the most prominent and recurring use cases were identified and user personas were developed, capturing their general work flows and experiences as user journeys. The four user personas were; urban planner, land planning officer, infrastructure planner and civil engineer. These users are directly impacted by the data and thus focused upon for further investigation.

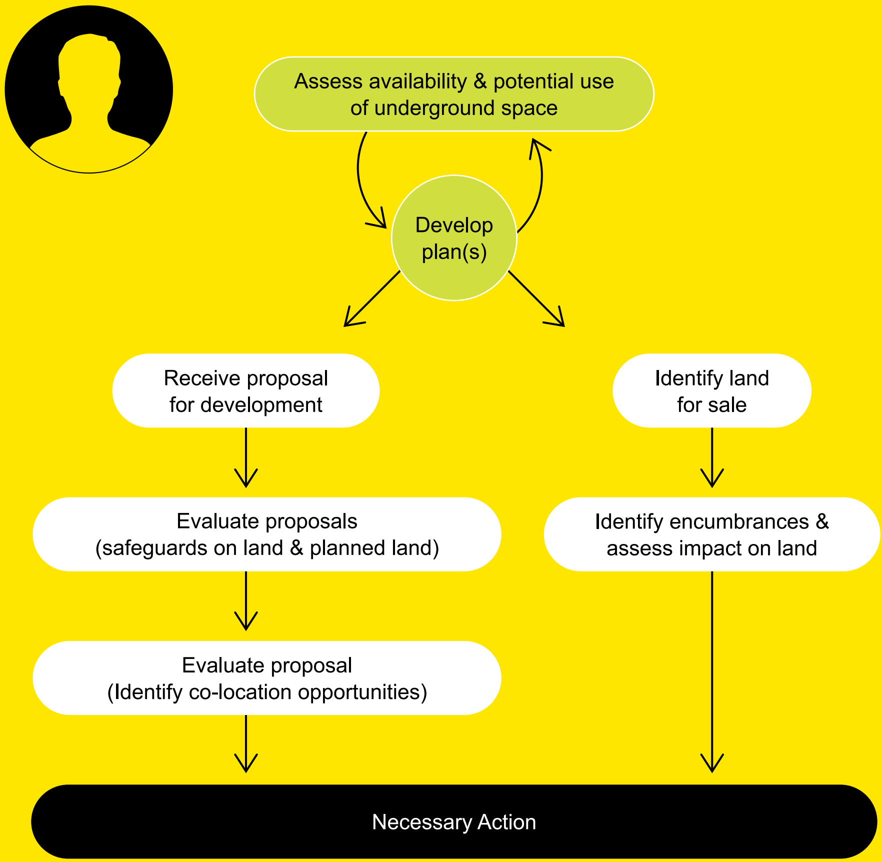
Persona[1]

Collin Leong

User Profile

53-year-old Senior Urban Planner

Together with his team, Collin plans the use of space — above and below the surface — of Singapore. Urban planning needs to manage an underground that is increasingly congested with building basements, transportation systems, utility infrastructure etc. He strives to ensure that the scarce land that is used, is utilised in the best possible manner, providing a continuously livable and resilient environment and infrastructure to Singapore's residents and businesses.



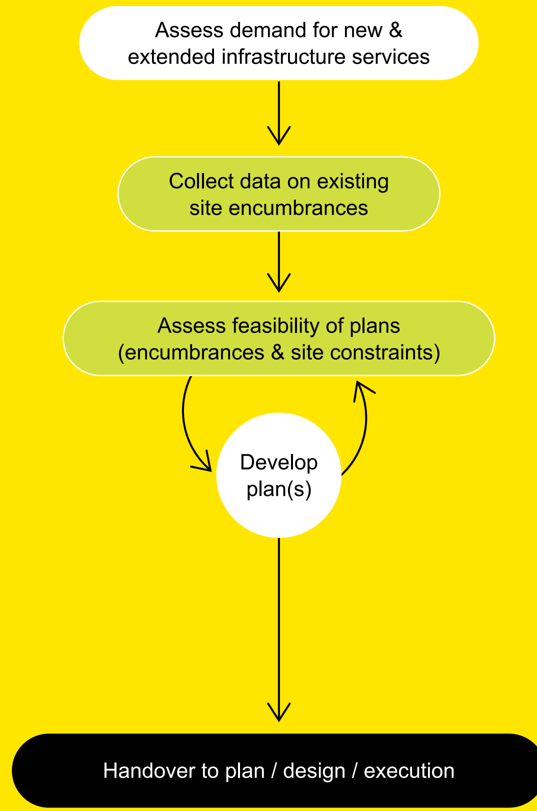
Persona[1]

Rania binti Abdul Majid

User Profile

35-year-old Infrastructure Planner

Rania works for a private utility company in Singapore. She carries out investigation and planning activities in order to support the development of new or extended utility network infrastructure. She strives to ensure the delivery of high-quality utility services for their customers are met, hence, establishing their advantage over competing companies, whilst also complying to regulations enforced by regulatory authorities and other infrastructure owners.



Areas where data beneficiaries/personas would require good quality data to discharge their work in the cycle of their workflow.

The case for a reliable digital twin

Journey Mapping[2]

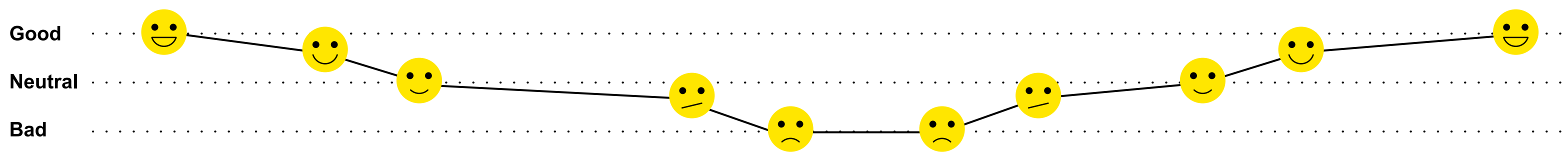
Persona

Collin Leong

Special policy for agencies vs agencies, agencies vs vendors, for plan purviews.

An inter-agencies platform for data sharing and visualisation.

Phases of User Experience

	Preparation	Survey	Integrate	Evaluate	Feedback	Execute
Action	Presentation on updates of the master plan, incoming development proposal, future land sale. Team brief on workflow.	Team commences study of encumbrances for affected land. Retrieve data on existing underground utilities from government data portal.	Utility data is prepared and converted for analysis. All data is integrated into a common frame of reference for analysis using choice software.	Visualise plans/proposals. Analyse impact of plan on selected land and vice versa. Present and commit to chosen course of action.	Provide feedback to stakeholders.	Take necessary action.
Feeling						
Thoughts		Need to collect other relevant data for analysis (eg. land ownership, coinciding future plans/proposals).	Tedious process to prepare and convert file types, scales for proper analysis.	Advanced spatial analysis required. Would be useful if the data can be overlaid in 3D.		
Interests						
Plain Points				Demand aggregation can be laborious. (services required). Retriving of underground utilities from different agencies require clearance.		
Insights		Special policy for agencies vs agencies, agencies vs vendors for plan purviews. An inter-agencies platform for data sharing and visualisation.				
Opportunities						

Work Flow

Journey Mapping[2]

Persona

Rania binti Abdul Majid

Better control over data source/ownership, availability, accuracy, completeness, format and void of data entry duplication.

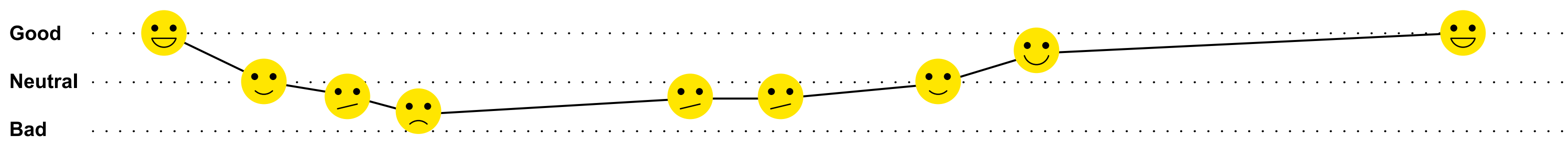
Workflow tracker between approval submissions on survey site digs for accountability and transparency on progress (approval and survey).

Have a system that tracks all updated and historical underground plans.

The case for a reliable digital twin

Phases of User Experience

	Preparation	Survey	Integrate	Evaluate	Feedback	Execute
Action	Assess demand for new and existing areas or customers to meet.	Together with a contractor, the team notifies all assets owners and collects drawings indicating the locating of existing utility infrastructure. Team applies for road opening permits to facilitate contractor's works in site.	A planned alignment is prepared based on the collected maps and results of the site feasibility study.	The plan is sent to all pertinent authorities and other land owners to seek approval. Based on feedback the plan is improved.		Approval is received from all authorities, take necessary action and handover to the project execute department to engage contractor to start.
Feeling						
Thoughts		Establish requirements for utility network extension, identify affected corridor and land owners.	Need to collect other relevant data for analysis (eg. land ownership, coinciding future plans/proposals).	Preparation of plan submission that contains the planned alignment, potentially, evidence of non-conflict with existing encumbrances and land boundaries.		Plans need to be correct as of done date. Check for concurrent updates elsewhere.
Interests						
Plain Points						
Insights			Require better data source/ownership, availability, accuracy, completeness, format and void of data entry duplication. Studies require proper database that describe the attributes of datassets given the different accuracies and sources of data.	Workflow tracker between approval submissions on survey site digs for accountability and transparency on progress (approval and survey).		
Opportunities			Ability to review and share data service works in 3D visualisation.	A tailored data submission template for different field of work/projects.		A system that tracks all updated and historical underground plans.



Work Flow

The engaged beneficiaries universally indicated the need for sufficiently accurate, up to date, and complete digital data describing the three-dimensional location and spatial extent of subsurface utilities within or near planned developments. Commonly mentioned supplementary information needs include land ownership, reserve boundaries, ongoing and planned developments, potential encumbrances and obstacles above and below the ground such as buildings, tree roots, and road reinforcements. This could be seen as a pattern from the nature of work in the public sectors is centred

An interesting observation emerged between the public and private sector users which suggests that public sector stakeholders strongly value data quality and accuracy whereas private sector participants emphasise efficiency of operation.

more on desktop data analysis and effects on the entire infrastructure network. Private sector users emphasised data needing to be up to date and called for solutions for effective detection of infrastructure prior to installation.

Based on the findings, reliable information on subsurface utilities can be expected to improve the approval, planning, design, execution of infrastructure and other development projects. Upfront knowledge on existing utilities and their setback distances, site conditions, and ongoing and planned nearby developments increases the chance of proposed plans to be feasible and not impact existing infrastructure or future plans for developments. This results in fewer setbacks, delays, incidents during and after the execution phase. Furthermore, such information enables urban planners to achieve a better use and allocation of underground space, for example by co-locating services and ensuring that future development plans are safeguarded.

However, critical challenges need to be overcome to achieve these benefits. Users mentioned project setbacks due to a lack of data quality. Information on the location, dimensions, and properties is often inaccurate or lacking, occasionally discovered late (during trial trench) or at times misinterpreted or misrepresented. Location information often lacks the third dimension while the underground is a dynamic, three-dimensional space. Another concern shared was the lack of a consistent and up to date source of information across various collaborating or interacting parties and the lack of quality metadata. This results in a continuous need for cross-examination and comparison of data to ensure it is the latest and best version in addition to repeated verification of known accurate locations.

With the availability of reliable information, we expect benefits to be reaped in numerous use cases across various users. These include planning and safeguarding of land use, identification of co-location opportunities, planning of new infrastructure or other developments, permitting and approval, coordination of works, and multiple stakeholder communications.

Within the context of an ever-developing underground, it is evident that we, together with all involved stakeholders, are working towards a goal that is exciting and relevant. We are heartened by the enthusiasm and efforts of the engaged users to improve their practices and it is with their support that our conviction will endure and mature.

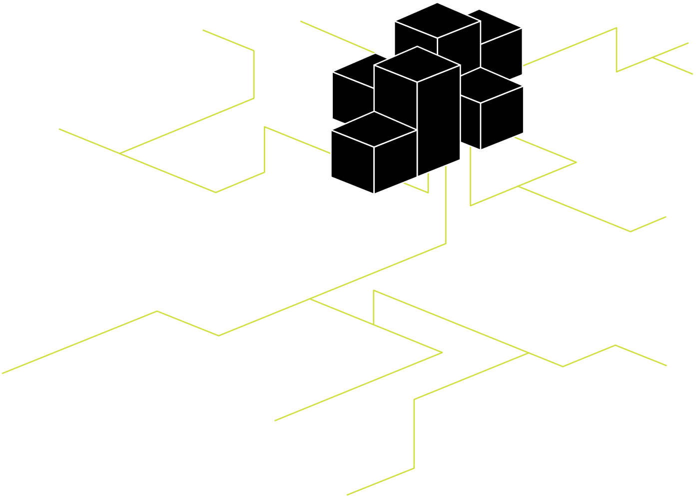
1 Persona(s) - (1983) Alan Cooper, a pioneer software developer, proposed the concept of a user persona. Personas are fictional representations and generalizations of a cluster of your target users who exhibit similar attitudes, goals, and behaviours in relation to the product. They're human-like snapshots of relevant and meaningful commonalities in customer groups and are based on user research - (January 28, 2018) Kim Flaherty.

2 A journey map is a visualization of the process that a person goes through in order to accomplish a goal. In its most basic form, journey mapping starts by compiling a series of user actions into a timeline. - (1998-2021) Nielsen Norman Group.

The case for a reliable digital twin

Reliable data for a resilient and connected smart city

Tan Boon Huat
Senior Vice President
Operations and Customer Experience
SPTel



Underneath Singapore is a living network of pipes and ducts that form the infrastructure backbone of Singapore. This ever-changing network sees new connections, diversions and rerouting taking place every day.

For a Business Class Digital Network provider like SPTel, an understanding of the location of these underground pipes is crucial for us to deliver resilient, ultra-low latency performance connectivity. A wrong cut could result in service outages for critical services that rely on us for connectivity.

That is why we expect the Digital Underground project to make a huge impact on our industry. By tracking and tracing newly installed pipes from the different infrastructure owners in Singapore and providing up to date 3D data to 3D visualisation and planning software, we will now have unprecedented clarity and certainty of our underground infrastructure.

The benefits are multifold. Building owners and government agencies will be able to use this 3D underground utility data to plan for a smart nation future that will increasingly rely on resilient connectivity. For SPTel, we believe that with the 3D mapping of infrastructure, we will be better able to monitor the health of our pipes for on time and precision-based maintenance, fixing problems before they result in a major breakdown. We can also better plan for resilient services that is truly diverse, increasing our fibre path diverse offerings. As Singapore moves towards a smart nation, it is inevitable that more connectivity and fibre density will be required to power new solutions like 5G and IoT. The speed to market will also need to increase to stay competitive. This underscores the value of the Digital Underground project. SPTel is glad to see the project embarking on this valuable initiative that will take Singapore a step closer to our aspirations of becoming a smart city.

Reliable data for construction productivity

Shane Shi
Managing Director
HSC Pipeline Engineering

Imagine emergency earthworks that need to be done immediately. The earthwork contractor submits an online emergency application to the utility companies and receives an approval for works along with accurate and reliable 3D as-built information. With this information on hand, the contractor carries out the emergency earthworks with confidence that there is little to no risk of damaging any other utilities in the vicinity.

> Singapore's utility services are among the most reliable in the world and the respective agencies are doing their best to maintain their performance.

Aside from equipment failure or software related issues, the top reason for utilities disruption is earthworks that range from excavation, piling, soil investigation and even earth-rod installation. It is the top concern of utility owners to minimise damage to their utilities which directly affects their industrial and residential customers.

Some of the infrastructure can be upwards of 30 years old. The quality of older as-built information is unknown as most of the information was captured using less strict standards than today and reference street elements such as road kerbs which can change over time. Due to the lack of reliability of existing as-built data, utility owners require multiple trial holes to be excavated to ascertain the location of their utilities before the approval of laying new services.

As a contractor specialising in laying gas infrastructure, these increasing requirements directly affect our work in terms of cost, time and delays in utility laying works. We estimate excavation and resurfacing activities to cost upwards of SGD 100,000 per lane-kilometer. Our ability to efficiently perform our work have been further complicated by additional restrictions imposed due to Covid-19 have caused a decrease in available manpower in Singapore, further pushing back project schedules and completion dates.

With the availability of reliable digital information, we expect overall productivity to increase. All utility locations could be made available for contractors to purchase and plot into a 3D environment. For utility owners, knowing that their networks are safe and unlikely to be disrupted, the processing of earthworks applications can be reduced, saving on labour costs to monitor and witness trial holes. For contractors like ourselves, the approval for new utility laying or earthworks can be obtained based on reliable information. Construction can be carried out as per approved plan, greatly reducing the cost involved in getting approvals for new utility construction and conducting trial hole excavations.

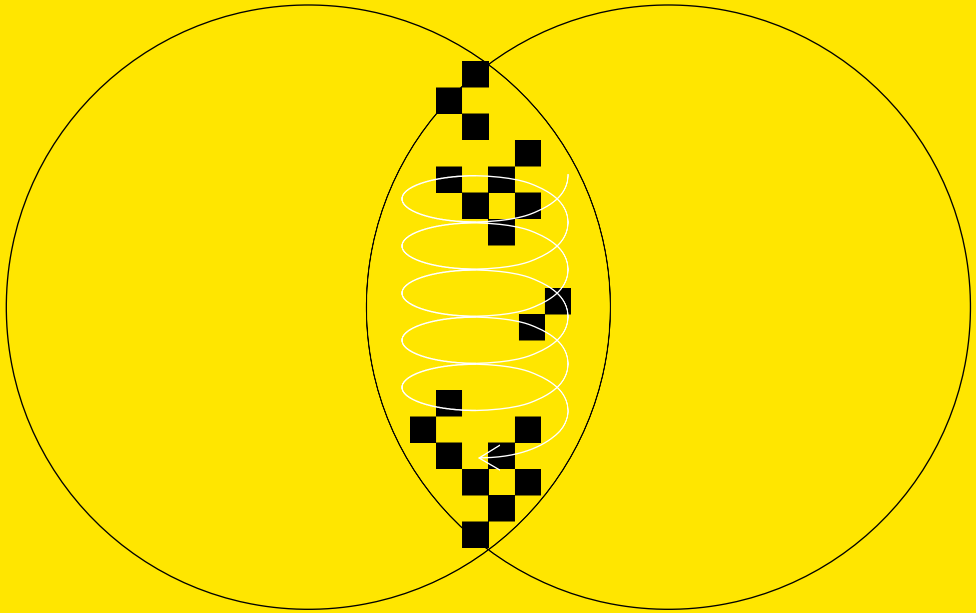
Gas pipe laying works on Cantonment Road.

Trial trench

Imagining a digitally enabled future

An accurate virtual representation of all subsurface utilities in Singapore can improve and enable digital workflows for planning and development. Due to the dynamic and unseen nature of underground space, building, maintaining, and utilising such a twin requires new approaches to the mapping and representation of urban underground space.

Digital Underground: Research collaboration towards a reliable digital twin



The Digital Underground project is a collaboration between the Singapore Land Authority and Singapore-ETH Centre towards a reliable digital twin of subsurface utilities for planning, land administration, and construction.

Through research, the project aims to address the most pressing challenges that prevent data on subsurface utilities from being consistent, accurate, complete, and up to date.

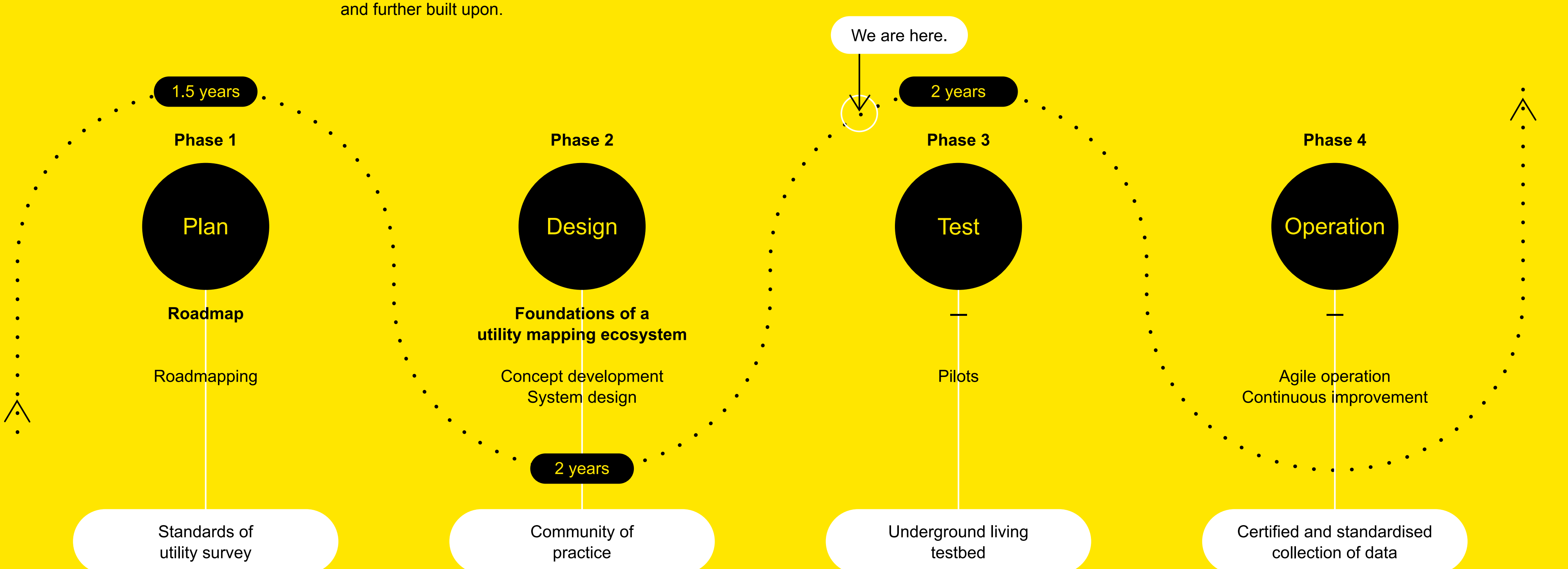
Through collaboration with stakeholders from public and private sectors, the project aims to deliver well-supported and feasible recommendations.

A phased approach towards a reliable digital twin

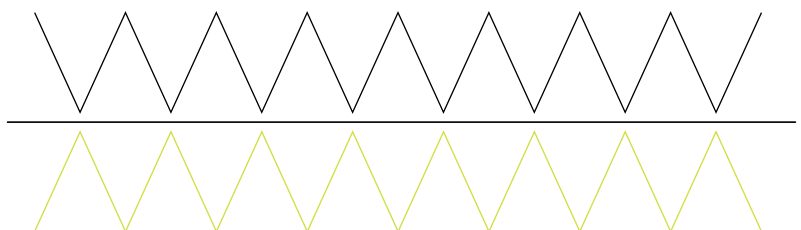
The project was established in 2017 following the release of Singapore's standards and specifications for utility survey. The first phase of the project sought to develop a plan — a roadmap — to work towards its goal of a sustainable utility mapping ecosystem. Phase 2 — the stage of the project that is covered in this booklet — aims to translate that plan into a more concrete design of the workflows, processes, and supporting instruments that are needed to realise it.

In future follow-up phases, the project aims to test and refine the designed concepts and support the government of Singapore on its journey towards realisation of a reliable digital twin. Throughout the various stages of the project, enabling infrastructures and instruments are progressively established and further built upon.

	Phase	Theme	Enabling infrastructures and instruments
2017	**Phase 0**	—	Standards and specifications
2017 – 2019	**Phase 1** PLAN	Roadmap	Roadmap
2019 – 2021	**Phase 2** DESIGN	Foundations of a utility mapping ecosystem	Community of practice
2021 – 2023	**Phase 3** TEST	Workflows for reliable data quality	Pilot testbed
	Phase 4 OPERATION	Agile operation & continuous improvement	End-to-end digital workflows for subsurface utility data



Digital twinning the underground: Vision for a mirror world of the underground



The underground of Singapore is in a constant state of flux. Day in day out, subsurface utilities and other underground infrastructures are installed, diverted, replaced, and removed. This makes planning, developing, and managing underground space an extremely daunting task that is fraught with risk and uncertainty.

How do we ensure that data beneficiaries have access to the most reliable, complete, and accurate data on subsurface utilities at any given time? How do we establish a true digital twin — a virtual representation that accurately mirrors its physical counterpart as it progresses through each stage of its life cycle?

Digital twinning as a new paradigm for mapping the underground

Conventional mapping approaches — in particular for above ground assets — tend to rely on the one-off capture or collection of data at infrequent intervals. For unseen underground assets, these approaches are practically unfeasible and economically unviable, resulting in data that could be outdated as soon as or shortly after they are produced.

A more dynamic approach is required. With qualified professionals — developers, contractors, and surveyors as its *sensors*, a digital twin needs to be established that continuously ingests and integrates the latest information and observations on subsurface utilities. The digital twin brings the results from various connecting workflows such as infrastructure planning, as-built surveying, and Subsurface Utility Engineering together in a single, consolidated environment. This enables a continuously up to date and complete digital twin that would steadily improve subsurface utility data:

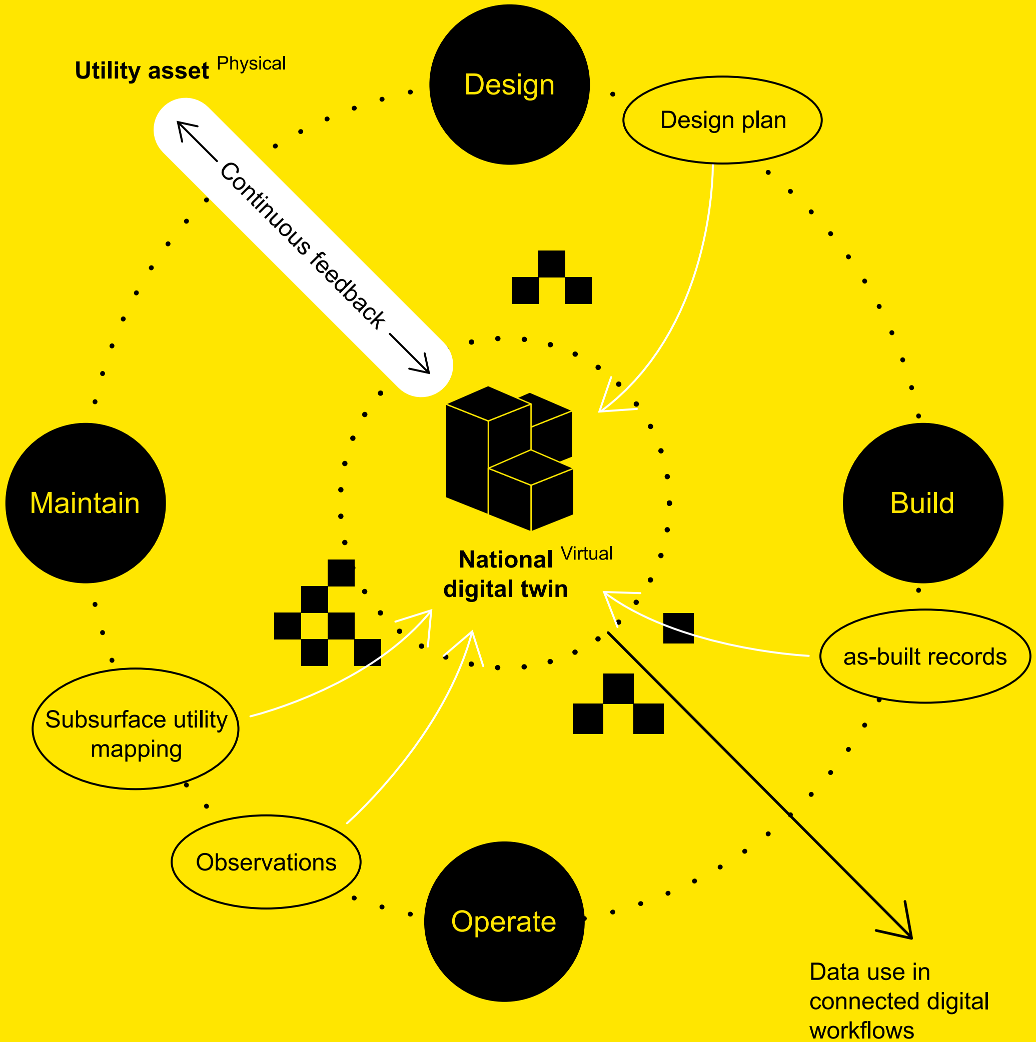
→ From planned to proposed to as-built representations;
→ From previously unknown to known quality;
→ From inaccurate to accurate locations.

Gradual and continuous enrichment of an authoritative source of data

Professionals + technology as ‘sensors’

Collect. Measure. Improve. Share.

From mapping to digital twinning



While the Digital Underground project mainly focuses on data and their quality, it is essential to keep the end user in mind and continuously demonstrate the value of a reliable, three-dimensional digital twin.

As a distillation of use cases and user experiences, use case demonstrators were developed to document, apply, and validate what was learned from user engagements and showcase a digitally enabled future for Singapore, going underground.

Michelle Chan Mei Har
Isaac Lu
Hilal Fitri bin Rohaidi
Singapore-ETH Centre

How reliable data improves digital workflows

Two demonstrators were developed using a storytelling approach. Through the eyes of users, it envisioned how they would perform their work. Two user personas — the land planning officer and infrastructure planning officer — were selected and their workflows and use of subsurface utility data demonstrated.

The first demonstrator showcases how a land planning officer can utilise a digital twin on subsurface utilities for the evaluation of utility development proposals. It is the goal of the officer to analyse and understand all aspects of the plan in relation to the land under their purview, existing underground encumbrances, regulatory constraints, and future plans in order to make an informed decision whether the proposed plans can be approved. Additionally, this presents an opportunity to evaluate potential space for co-location of new and existing utilities.

In the second demonstrator, information on subsurface utilities is used to support the planning of an infrastructure planner working for a utility company. On top of the considerations in the first demonstrator, the officer would also study in greater detail its underground surroundings to ensure plans adhere to all neighbouring assets restrictions and the project restores all above ground conditions back to its original state when completed.

The demonstrators serve as vivid documentation of the needs and aspirations expressed by current and future data beneficiaries and display how subsurface utility data — together with other data sources — can be used to build urban-scale digital twins that empower digital three-dimensional workflows of the future. They will continue to serve as a reminder of the goals we are working towards.

Demonstrator visualisation example (Fig. 1-7)

Fig.1
Review of road reserve lines

Fig.2
Review of areas where specific restrictions apply (e.g., tenancy agreement, notice period of works etc.)

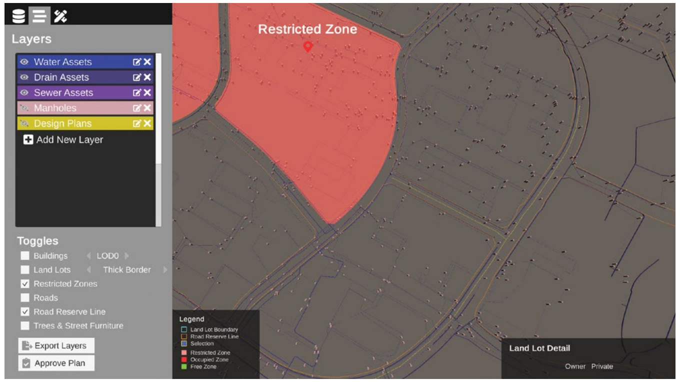


Fig.3
Review of minimum required clearance from regulatory areas and existing underground infrastructure

Fig.4
Review of conflict areas (highlighted in yellow) between proposed plans and any infrastructure or regulatory constraints.

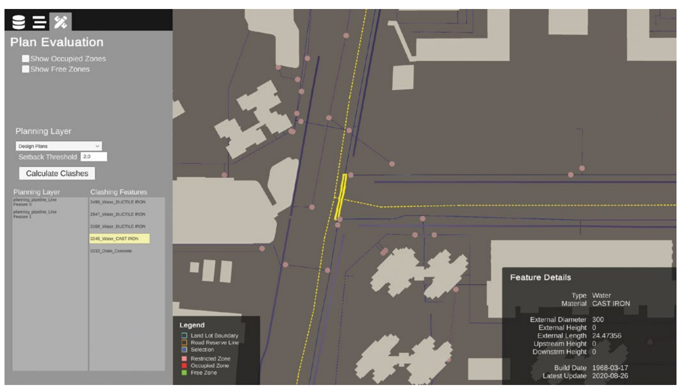


Fig.5
Review of potential co-location areas

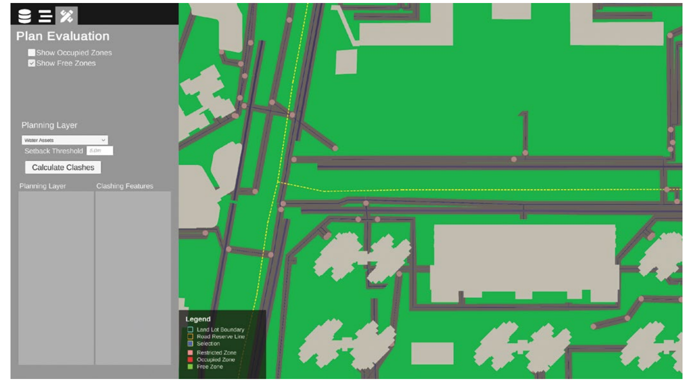


Fig.6
Review of above ground conditions

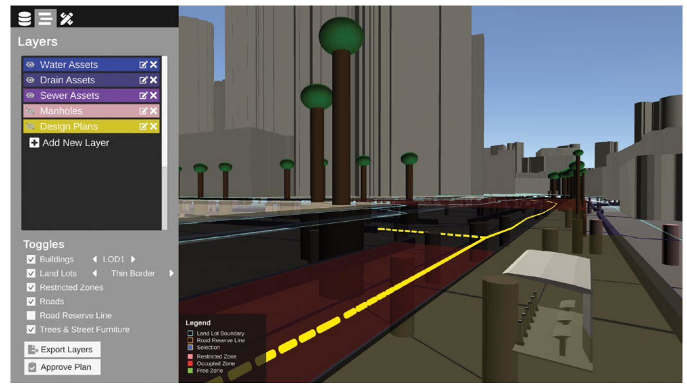
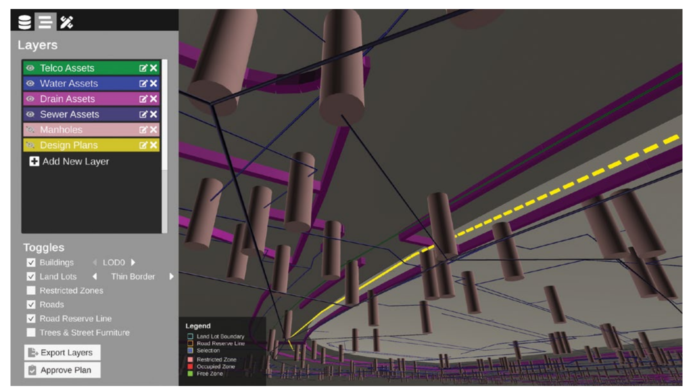


Fig.7
Review of plan and all other underground infrastructure assets



A digital underground twin for Planning Zürich's Urban Landscape

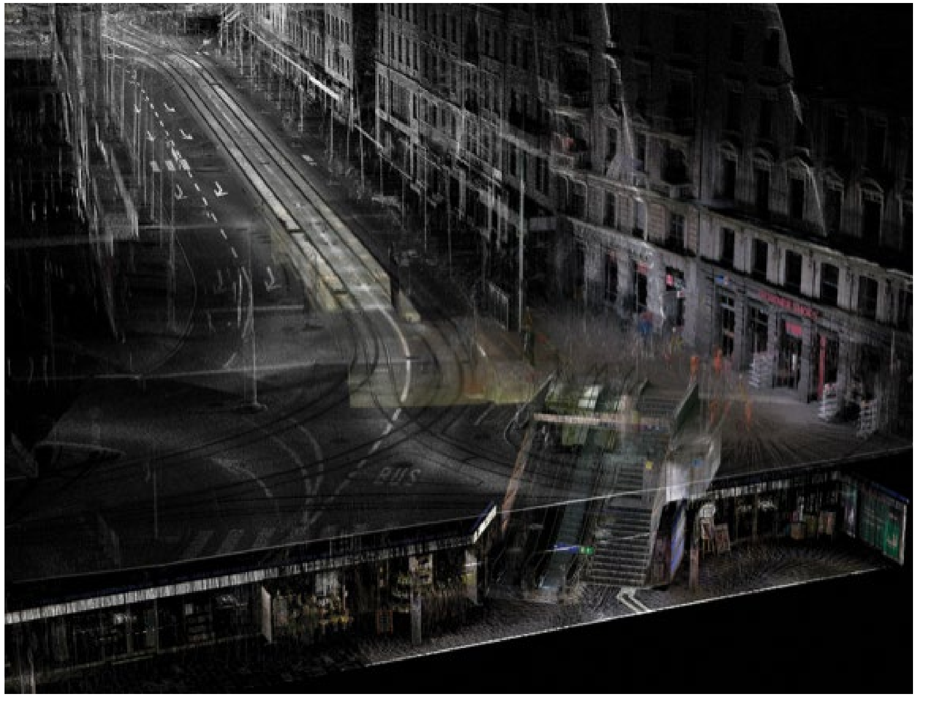
Matthias Vollmer
Research Associate,
ETH Zürich / Director,
SCANVISION

Due to a changing climate and the required planning of urban landscape, there is a need to know how artificial and natural structures spread throughout the underground and how they can form a successful coexistence with those above the surface.

A new perception of the city as one interactive space, above and below the surface, is necessary. The "Zürich: Underground and Urban Landscape" project, a collaboration between ETH Zürich (D-ARCH) and the City of Zürich (GeoZ), supported by the Smart City Lab Zürich, investigates the subsurface and corresponding urban landscape by visualising geospatial data.

The three-dimensional point cloud representation from Laser Scanning marks a paradigm shift in recording our visible environment and forms the base of a rich city model. It enables a detailed representation of the complex urban landscape including its vegetation and lends the surface texture of the model an almost haptic quality. At the same time, it enables spatial experience in motion; an essential aspect for the conscious perception of space and temporality in a model.

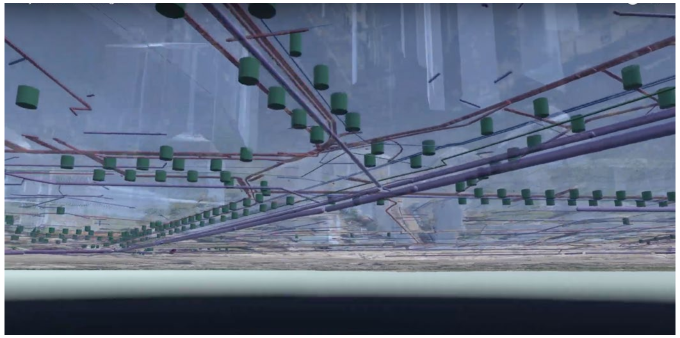
Seamlessly connected point clouds from above and below the surface in Loewenstrasse, Zürich. Image Matthias Vollmer



Imagining a digitally enabled future

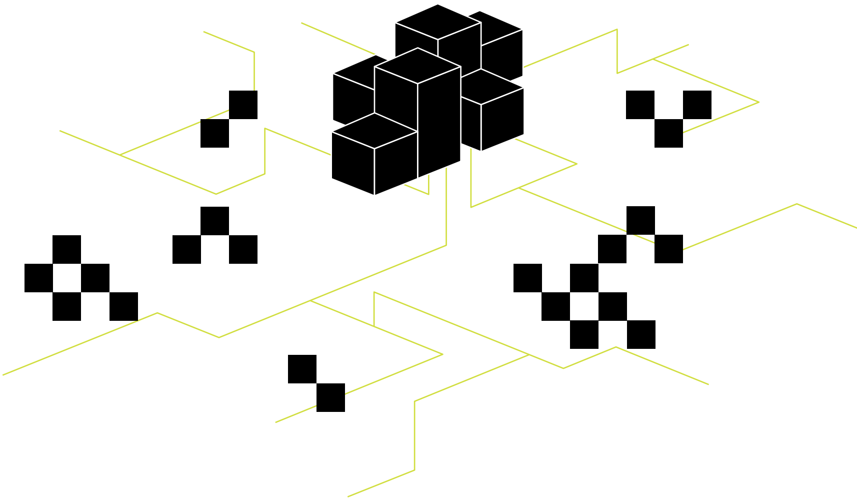
While extensive and detailed models of the above ground urban landscape are available, we lack such models of the underground. In Zürich, an extensive utility cadastre describes the public underground. Unfortunately, the data often lacks depth information necessary for its transformation into 3D. The contrast between advanced and precise 3D models of the above ground urban landscape and the complex two-dimensional overlay of different underground structures creates a diffuse image while shaping the perception of the subsurface.

In an approach to overcome this gap, geospatial datasets were compared to the respective building regulations and the involved people were interviewed. Missing information was supplemented and, with the help of parametric data processing, assembled into 3D shapes.



3D models representing underground utilities. Image: Matthias Vollmer

The integration of existing data from the field of landscape planning into the created model has quickly pointed out missing data necessary to produce a satisfactory output for a useful underground model. In the future, additional data sources describing the underground such as tree roots need to be considered to be included to aid future planning and better estimate spatial needs underground.



Design of a utility mapping ecosystem

Reliable information on subsurface utilities requires an integrated approach. To help establish the foundations of a sustainable utility mapping ecosystem, Phase 2 of the Digital Underground project developed a broad set of recommendations on data governance, data capture, data management, and capacity development and established the Digital Underground Connect community of practice as a key enabling infrastructure.

Digital Underground Phase 2: Foundations of an ecosystem

Digital Underground Phase 2: “Foundations of a sustainable utility mapping ecosystem” follows up on the recommendations delivered upon conclusion of the first phase and set out to develop and recommend the foundations of an integrated approach.

Digital Underground phase 1 concluded with the delivery of a roadmap that signalled a clear message: Reliable information on subsurface utilities can only be established and sustained through an integrated, “whole ecosystem” approach. An interconnected framework of effective policies and processes, capable people, and appropriate digital technology is required to achieve the desired successful transformation.

Phase 2 of the Digital Underground set out to make a contribution to the establishment of a sustainable utility mapping ecosystem. Through research, engagement, and collaboration, the team produced the following results:

1 **Data governance**
A proposal for a new subsurface utilities data governance framework, detailing roles and responsibilities, key activities, and a master data management architecture aimed at improving data quality and data availability.

2 **Data capture**
Recommendations for the extension of Singapore’s utility survey standards as a central regulatory instrument that describe new data capture scenarios, techniques, and a common data submission format.

3 **Data management**
Specifications for and a prototype of a digital platform that serves as a technical enabler for data quality management, establishing a common point of submission and tools for quality control and consolidation of all data on all subsurface utilities in Singapore.

4 **Capacity**
A competency framework and training needs analysis to support the development of necessary skills and competencies of the various professionals that the ecosystem relies on.

5 **Community of practice**
Establishment of a community of practice to facilitate knowledge sharing, improvement of practices, and onboarding of professionals.

Subsurface utility data governance provides practices throughout the entire lifecycle of subsurface utility data with the necessary foundation, strategy, and structure needed to continuously ensure that the data is managed as an asset and transformed into meaningful information that is valuable and beneficial to planners and developers in Singapore.

A data governance framework was developed to support the development and deployment of an effective data governance program.

Towards mature governance of subsurface utility data

Why governance of subsurface utility data matters

The availability of reliable information on subsurface utilities is of vital interest to Singapore towards realising its ambitions of going underground. To ensure produced data is of sufficient quality, established as a reliable source of truth on utilities for planning, land administration, and development, readily available, and responsibly used, a data governance framework was developed. The framework describes the foundation for development and deployment of a program that ensures data is managed as an asset and transformed into meaningful information.

Singapore's commitment towards proactive and mature data governance

There is no doubt that Singapore is on the right track towards mature governance of subsurface utility data and underground information in general. Virtually all stakeholders are aware that much of the available information is unreliable and that this has repeatedly led to losses of time, money and opportunities. Moreover, "whole-of-government" underground information working groups and the introduction of nation-wide utility survey standards display a strong intent to address data-related issues proactively.

Despite such positive efforts, it is uncertain whether these interventions have resulted in the desired or expected change. Successful practices of data production, data management, data sharing, and data use still largely depend on the commitment and effort of individual land administrators, asset owners, contractors and surveyors and have not been consistently established for all utilities or for everyone involved across the city-state. As a consequence, significant resources are invested daily to work around the lack of reliable information, with no clear path towards sustainable resolution and improvement.

In contrast, a desired state of data governance is one in which strong buy-in and involvement exists among all stakeholders throughout the information value chain. Roles and responsibilities are clearly defined and fulfillable by capable organisations and individuals. Decision making is evidence-driven and the effectiveness of interventions monitored. Data definitions and quality rules are clearly and consistently defined. And data are continuously inspected and improved throughout their lifecycle.

A data governance framework to foster growth and continuous improvement

To support Singapore's growth towards a mature state of data governance and meeting its data quality and availability objectives, a data governance framework was developed based on local stakeholder contributions and exploration of overseas jurisdictions. The framework consists of the following elements:

- **Objectives and guiding principles.** The framework is aimed at achieving three objectives centred around data quality, the establishment of a reliable source of truth, and data availability. Throughout the development and operation of a data governance program, collective awareness, trust and continuous improvement remain key principles.

- **Performance indicators** to assess the effectiveness of the program and its interventions. These are
  (i) indicators of intrinsic data quality,
  (ii) indicators that relate to the outcomes of business processes supported by the data, and
  (iii) intervention-specific indicators.

- **Roles and responsibilities** that describe the roles necessary to achieve the program's objectives on the strategic, tactical, and operational level.

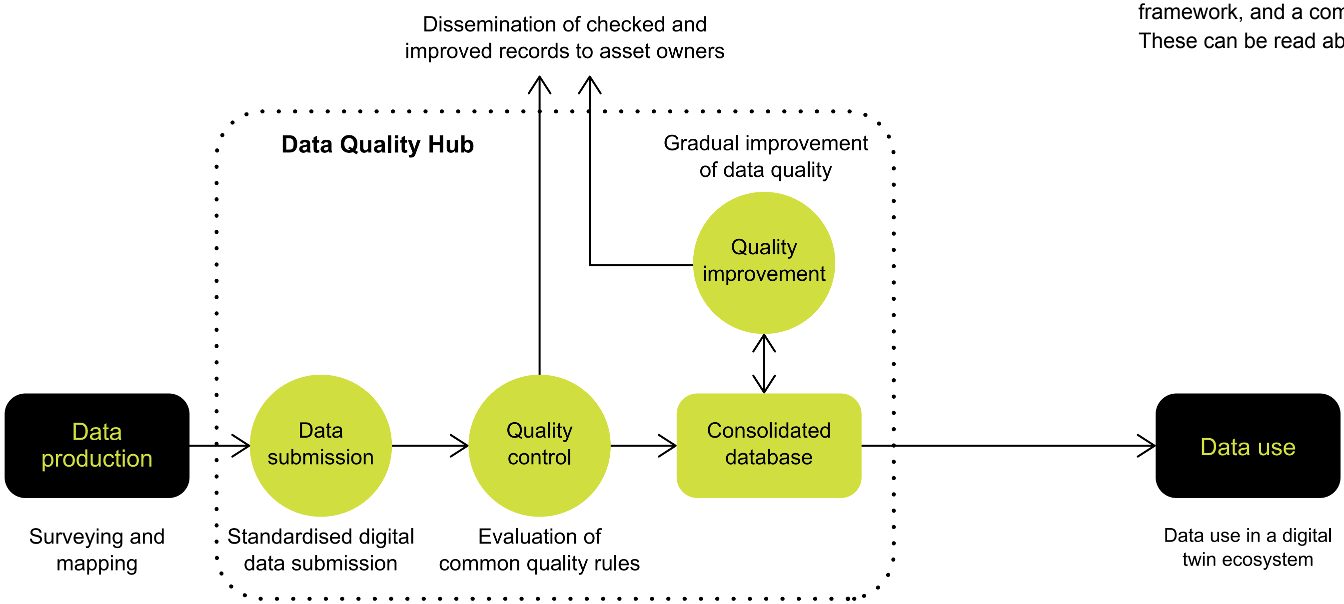
- I**nstruments and infrastructure** that are initially recommended to feasibly execute the data governance program ranging from policy and legislative instruments to technical and people-related ones.

- Recommendations for the gradual implementation of a **Master Data Management Architecture** necessary to establish a "golden record" of information on subsurface utilities in Singapore. Specifically, the proposed architecture introduces the concept of a national subsurface utilities "Data Quality Hub" for the improvement of data quality. While change is gradual, every step along the way adds value that is compounded for successful outcomes for the long term.

A national subsurface utilities Data Quality Hub

The proposed Master Data Management Architecture notably introduces the concept of a national *Data Quality Hub*. We define this as a system that consists of a consolidated database and data flows for data quality management that are designed to co-exist with and add value to Singapore's current utility data workflows. Specifically, it contributes the following improvements:

- Standardised digital submission of all newly captured data on subsurface utilities.
- Quality control of submitted data by evaluating a common set of rules for all subsurface utility data.
- Consolidation and integration of newly collected and legacy data for legacy data quality improvement and potential use of the data as a building block of a digital twin ecosystem.

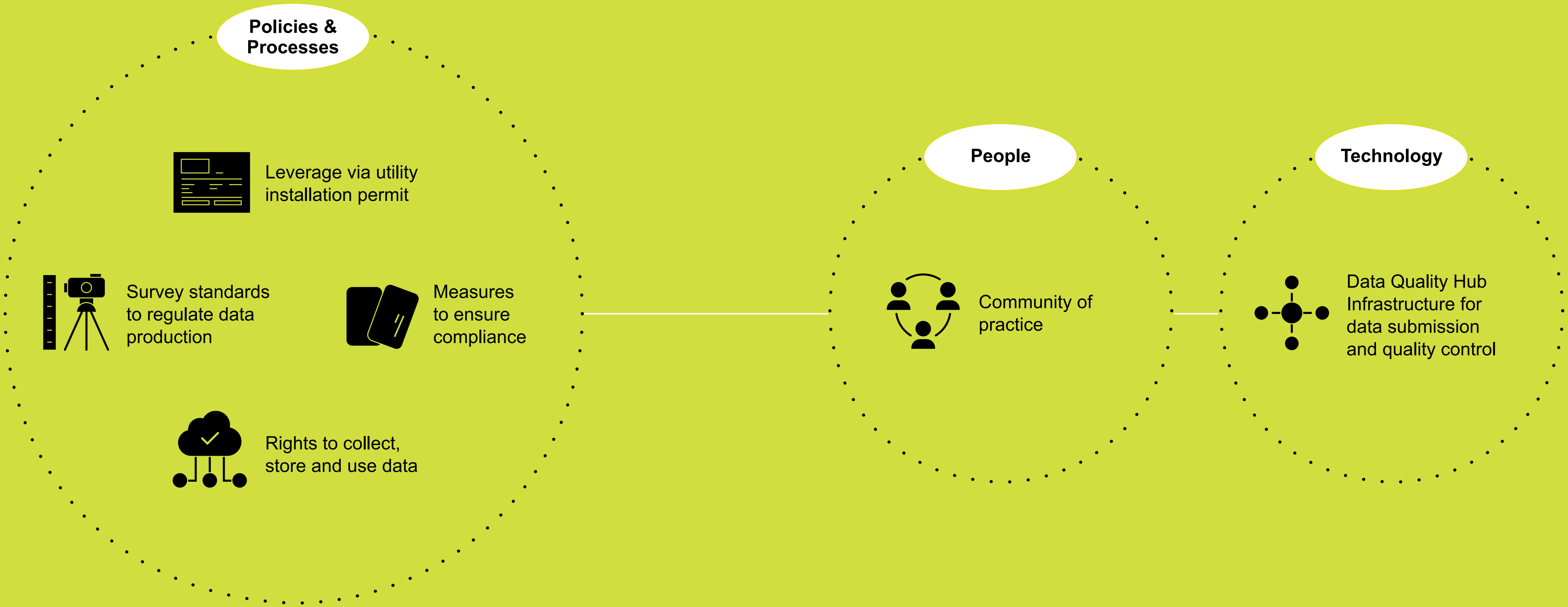


By placing the Data Quality Hub as far upstream as possible, the system and its operators are able to tackle data quality issues as early and close to the source as possible. While the system may require specialised expertise to function initially (e.g., to perform quality checks on incoming data), increased automation is expected to enable various stakeholders to use, participate, and contribute to the system.

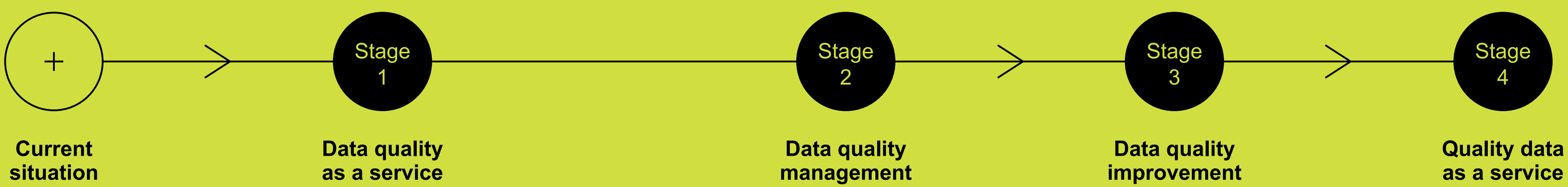
With its emphasis on gradual change, continuous improvement, and community involvement, the proposed framework complements Singapore's current efforts and leverages the awareness and desire to improve matters as shown by various stakeholders. To further complement the proposed framework, the Digital Underground project investigated, developed, and extended supporting instruments such as a prototype platform for data submission and quality control, survey standards, a training framework, and a community of practice. These can be read about in the next sections.

Design Of A Utility Mapping Ecosystem

Initial supporting instruments



Implementation plan for master data management



Improved practices for subsurface utility data capture

New and increased needs for subsurface utility data rely on robust and well-described procedures and practices. Through benchmarking and stakeholder engagement, a comprehensive set of recommendations for the extension and improvement of Singapore's utility surveying standards were identified.

Design Of A Utility Mapping Ecosystem

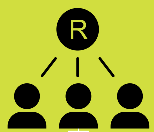
Since 2018, the Singapore Standards and Specifications for Utility Survey have been mandated progressively as part of all new utility development contracts and utility laying permits. The standards describe in detail what data needs to be captured, how it should be captured, and by whom, for the case of new utilities that were installed using an open trench method.

Regular review and revision of mandated practices are required to ensure that they are feasible and effective. Furthermore, a digital twinning approach to mapping the underground engenders new and increasing data needs. New and additional data capture scenarios need to be capitalised upon and supported by new techniques and capable professionals.

Through analysis of comparable standards, guidelines, and practices from overseas jurisdictions and engagements with various local stakeholders, the team identified a comprehensive set of recommendations for improvement and extension of current practices and procedures that include:

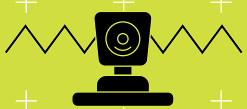
- The inclusion of additional data capture scenarios, such as the surveying of new utilities that are installed using trenchless methods and the surveying of existing assets prior to development.
- The inclusion of additional data capture techniques to support new scenarios, such as gyroscopic mapping devices and ground penetrating radar.
- The specification of a standard digital data submission format to streamline data collection, quality control, and data consolidation.

Define roles and responsibilities in the utility surveying process
A clear definition of roles and responsibilities to help ensure that all stakeholders can optimally contribute to the production of data of sufficient quality.

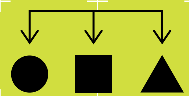


Cover additional scenarios for utility surveying
There are more data capture opportunities than newly built utilities using open trench methods. The standards should incorporate additional scenarios to cover alternative utility laying scenarios and the surveying of existing utilities.

Support additional techniques for data capture
The availability and advancement of new survey techniques enables professionals to capture data for current and future utility survey scenarios. These advancements also have the potential to to enable more productive data capture by professionals and with increased speed and accuracy.

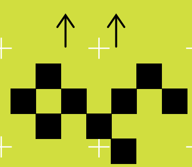


Incorporate additional types of utilities
Driven by new types of utilities being installed underground as well as a need to establish a complete map of all subsurface utilities, practices should incorporate the capture of additional types of utilities.

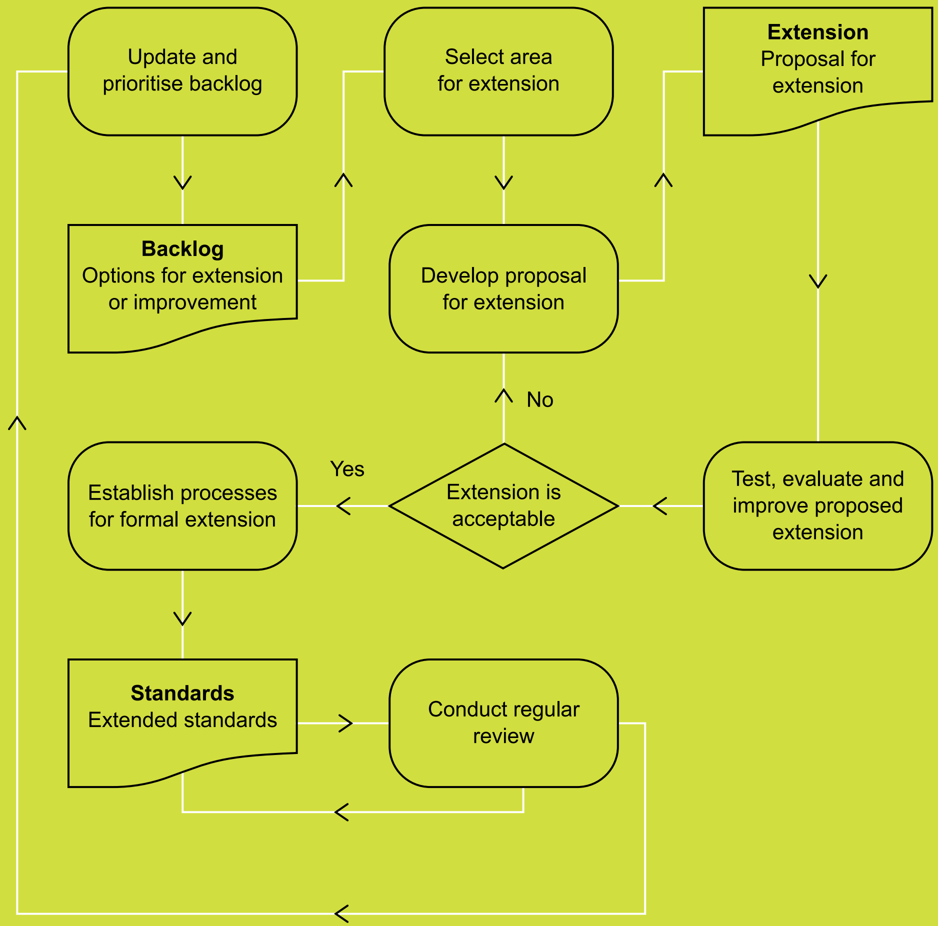


Reclassify data quality
Implement a confidence-based data quality level classification to express the reliability and accuracy of various data capture techniques and define quality control rules.

Standardise the data submission format
A common data submission format will enable the standardisation and digitisation of data submission and result in increased efficiency and data quality.



The standards can be utilised to establish a common baseline for all stakeholders to adhere to. Hence, the recommendations are accompanied by a proposal for an agile workflow for regular review, improvement, and evaluation of the standards and specifications in order to incorporate the proposed changes.



Improved practices for subsurface utility data capture

Capturing data from the trenches

The best opportunity for capturing accurate data on subsurface utilities is when they are exposed and visible. However, a limited window of opportunity and limited availability of qualified professionals for data capture may leave this opportunity unutilised. The advancement and availability of data capture solutions that are fast, affordable, and easy to use unlocks the potential of collecting rich and accurate data in a short amount of time.

Most new utilities are built using an open trench installation method. Additionally, a large number of trial trenches are dug every year to expose existing utilities and verify their location to support the planning and development of new infrastructure. In most cases, these utilities are exposed for a short amount of time before the trench is backfilled with soil. A continuous need for reliable data and the introduction of new data capture workflows — such as the surveying of existing utilities — create a potential mismatch between supply and demand of qualified professionals. These constraints of time and capacity can ultimately lead to data of insufficient quality. Solutions are needed that leverage the available capacity on site and increase the productivity of Singapore's Registered Surveyors.

New and upcoming surveying solutions offer the promise of rapid, remote, and accessible data capture. Visual positioning solutions such as the Leica GS18I offer traditional GNSS RTK positioning combined with an imaging device that measures positions from images. Concurrently, we are witnessing an increase of solutions that utilise low-cost, handheld devices to capture survey-grade data using photos and videos.

Data capture using a smartphone

Design Of A Utility Mapping Ecosystem

Design Of A Utility Mapping Ecosystem

Image-based measurement of exposed utilities using the Leica GS18I

Together with the solution providers, HSC Pipeline Engineering, and Jimmy Tan Registered Surveyors, the team conducted a short series of trials to develop hands-on experience using the solutions and evaluate the workflows and their results. Within the span of a few minutes per site, a total of three sections of newly built utilities and three trial trenches were surveyed and subsequently mapped. The trials demonstrated that valid alternatives to conventional surveying techniques exist and are able to successfully alleviate challenges in reliable and accurate data capture.

3D mesh model of a newly installed gas pipe

Point cloud of captured trial trench with georeferenced coordinates

Improved practices for subsurface utility data capture

Embracing technology advances for surveyors of the future

Jimmy Tan
Director
JTRS Registered Surveyor

Established in 2009, JTRS Registered Surveyor is a professional land surveying company based in Singapore that provides a wide variety of 3D laser scanning, land survey, aerial mapping & inspection, photogrammetry and imaging services. As a company, we are constantly on the lookout for innovative, technological and creative ways to conduct surveys. This allows us to deliver high-quality and accurate results to our clients.

Since 2018, Registered Surveyors in Singapore are required to perform the as-built surveys of all newly built utility structures for water, sewerage, drainage, telecommunication, electricity, and gas. Due to various challenges and constraints, it is difficult to conduct the survey according to the standards, using the right techniques, and by the right person. Such practices could result in information that is insufficiently accurate, unverifiable, and ultimately difficult to rely on for professionals using the data.

For us to adequately address such challenges, grow and sustain our business, and meet the demand for increasingly accurate and precise data, it is vital that we stay abreast with the latest advances in data capture technology. These help us to increase productivity and reduce manpower overhead costs.

New technology such as the Leica GS18 I GNSS RTK rover with visual positioning has helped to dramatically increase efficiency by enabling us to measure hundreds of points in minutes, reach previously inaccessible points, and capture points from a safe distance. For utilities, this now means that they can be accurately surveyed during the short time that they are exposed. And the dense point clouds captured can be used to trace results back to the raw scan data for verification and produce high fidelity 3D models of the pipes and manholes.

Besides adopting new technology, it is important that we constantly reassess the role that we need to play as surveyors within the larger ecosystem. With an increasing demand for digital data, scarce qualified capacity, and increasing democratisation and commoditization of technology, it is as important as ever to keep an open mind and encourage collaboration with other stakeholders while keeping up our standards for high quality and reliable data.

Image-based measurement of exposed utilities using the Leica GS18I

An accurate 3D model of utilities captured in a short amount of time for maximum traceability

Improved practices for subsurface utility data capture

BIM modelling of existing utilities by open trench survey

Mak Weng Tat
Director
Chartered Survey Services Consultants Pte. Ltd.

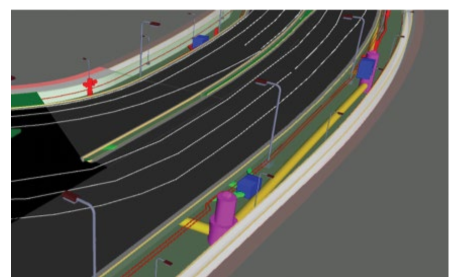
Building Information Modelling (BIM) is a key technology driver to improve the level of productivity and coordination in the construction industry. BIM models are typically used to benefit construction projects in the planning and design phases. However, when BIM is used up to the implementation stage and beyond, the benefits, due to its capabilities to visualise, store, and reuse information, are extended to other stakeholders and projects.

Design Of A Utility Mapping Ecosystem

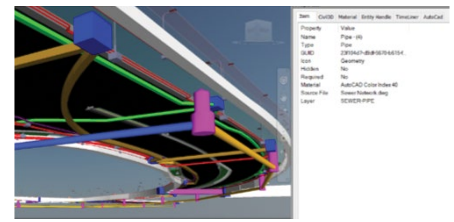
Recently, the location of existing underground utilities in a new town of Singapore was captured to support the planning of new infrastructure. Through trial trenching, the routing and depth of existing underground utilities were traced. All information was consolidated in a BIM model which was used as a reference for planning the new utilities. As the existing utilities were mapped out, the accuracy and other details were recorded. Different networks were organised in layers and colours attributed to support visualisation and use.

By properly georeferencing the utilities by assigning the correct Survey 21 (SVY21) coordinates with reference to the Singapore Height Datum (SHD), the BIM model can be combined and overlaid with other information to support planning tasks. For example, it can be used with topographical survey information of the ground, new proposed building developments, and many other sources of information. Using the available information, infrastructure planners were able to efficiently prepare an implementable plan for the soon-to-be-built utilities.

Image: Chartered Survey Services Consultants



Capturing the location of new and existing underground utilities in digital formats such as BIM models not only establishes a good reference for infrastructure planners. The information can also be passed down to the contractors that are tasked to perform excavation and utility laying works to prevent excavation damage, for example by enabling them to produce complete and up to date plans or visualising the data on site using techniques such as augmented reality. Furthermore, the information can be stored and made available to other planners and engineers who would eventually utilise the same site for their own projects.



As Singapore increases its underground development, the use of BIM has never been more necessary in understanding and documenting the use of underground space. As Registered Surveyors, it is essential for us to continue to improve our knowledge, skills, and competencies to meet the growing needs of our city-state.

Shane Shi
Managing Director
HSC Pipeline Engineering

Improved practices for subsurface utility data capture

Utilising Ground Penetrating Radar for data quality improvement

One possible way for utility owners to reconcile legacy data is to survey utilities exposed by trial hole excavation. Contractors are required to excavate trial holes to positively identify existing utilities as part of the earthwork requirements. However, currently no requirements to survey trial holes exist, leaving a potential opportunity to assess and improve legacy data unutilised. Exposing and surveying trial trenches poses an astronomical cost to any utility owner, relative to the benefits that it might provide.

However, additional and supplementary data capture techniques may be utilised to improve legacy quality data with little cost impact to utility owners, enabled by capable contractors and utility owners with the use of rapidly advancing technology. For our work, Ground Penetrating Radar (GPR) is proving to be an increasingly useful geophysical technique, allowing us to detect and locate underground services with a simple scan, reducing the need for trial holes.

A common view exists that GPR technology is unreliable. Data acquisition and processing is labour-intensive and therefore not worth the investment, limiting adoption. A clear grasp of how GPR works and the ability to select the right equipment and understanding the real limitations of the technique are absolutely essential for both the GPR operator and to the client requiring the information from the GPR survey.

Furthermore, with emerging technology such as 3D GPR mobile mapping platforms like IDS GeoRadar's Stream X and Stream Up, the speed of data acquisition and processing can be greatly improved. Through proper processing, we should be able to trace the alignment of the utilities from known points like manholes, chambers, stations, and reduce the number of trial holes.

The increased use of GPR will have both immediate and long-term benefits with minimal cost impact to utility owners. The acquired data can be provided to utility owners to allow them to approve earthworks in the vicinity of their utilities, reducing the number of trial holes required to be excavated. A second use for the collected data is for assessing and improving legacy data quality. When these processes are repeated in the long run and the resulting information digitised and consolidated, it becomes possible to have access to increasingly up to date and accurate information on subsurface utilities.

IDS GeoRadar Stream Up ready for testing in Singapore

Image:
Shane Shi

The need for a consolidated database for data quality management

A national mapping strategy for subsurface utilities

In 2019, the roadmap released by the Digital Underground project recommended a national mapping strategy of subsurface utilities that is based on three pillars:

1 **Establish a consolidated database**
A consolidated database for the purpose of data quality management with defined and measured data quality in order to assess and understand data quality, identify data quality issues, and identify potential interventions for data quality improvement.

2 **Ensure quality of new data**
Reliable as-built information for all newly built utilities enabled by strong, proactive quality controls at the front end of the information supply chain.

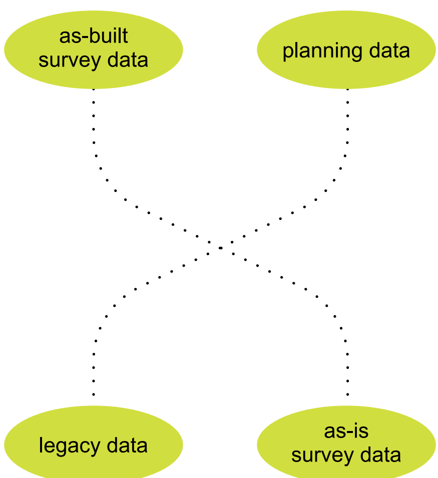
3 **Reconcile legacy data**
Gradual reconciliation of legacy data through opportunities to (re)survey existing utilities.

In Phase 2, the team set out to investigate and demonstrate how this could work. To this end, a prototype data quality management platform for the collection, storage, and integration of subsurface utility data and assessment of data quality was developed.

A consolidated database for data quality management

Data integration and defining data quality in a consolidated database

Dr. Yan Jingya
Singapore-ETH Centre



At the heart of the data quality management platform is a consolidated database of all subsurface utilities. At the conceptual level, the Underground Utility Data Model (UUDM) serves as a basis for integration of data from different sources which currently include legacy GIS and as-built GIS data produced directly from surveys. It provides a common description of the location, physical topology, and attribute information of water, sewerage, drainage, telecommunication, electricity, and gas utilities. Along with information on the utilities themselves, for newly built utilities, primary data and supporting evidence of the survey procedure can be integrated to trace back data to their source and evaluate data quality. In the future, the data model can be extended to incorporate new data sources such as plan and design data and the results from Subsurface Utility Engineering (SUE) surveys to be integrated with and connected to legacy records.

To provide a common definition of data quality, a data quality model was developed. The model breaks down data quality in various aspects which are defined by parameters. These are, for example, locational accuracy, attribute completeness, and format consistency. The data quality model was used to define and organise the conditions and rules for quality control and to develop a simple quality rating for data stored in the database.

Both developed models were utilised to support platform and database design on a logic level. Two workflows — one for the ingestion of newly captured data and one for the conversion and integration of legacy GIS data — were designed and implemented in the prototype platform.

A data quality model for subsurface utilities helps to

A consolidated database for data quality management

A digital workflow for the collection and quality control of as-built data

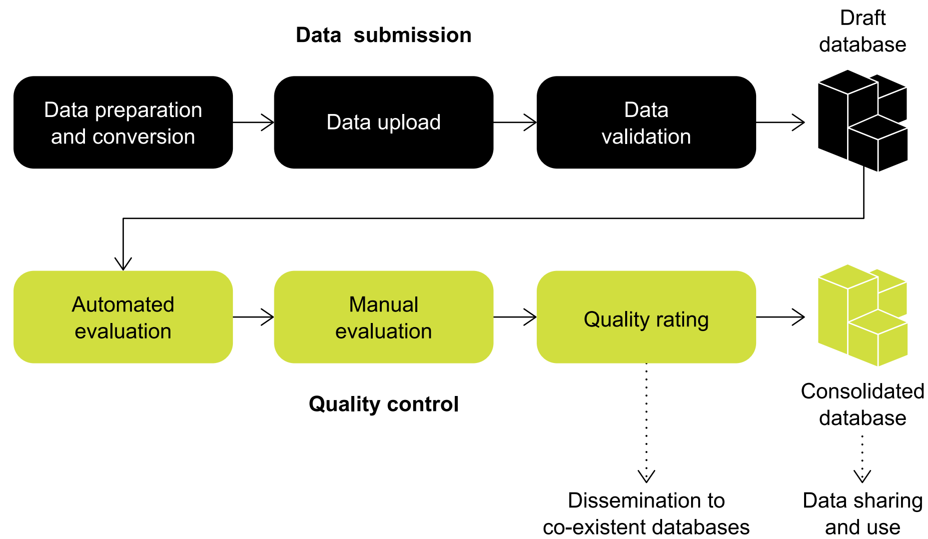
Dr Miao Yufan
Wu Hao
Singapore-ETH Centre

Since 2017, standards in place mandate highly accurate capture of the most common types of newly built utilities and its location. While data quality issues are best addressed as early as possible during or directly after data capture, the quality of such captured data is currently not extensively checked by utility owners and other organisations that mandate capture of such “as-builts”. This could result in data that is of insufficient quality and the uncertainty about the quality itself, thus leading to ineffective and inefficient decision making by planners, land administrators, and developers using the data.

We explored how a standardised digital data submission workflow can help to ensure data quality and increase confidence in the quality. A concept workflow was developed and demonstrated as part of a prototype data management platform. The workflow requires all data to be submitted by data producers in a single, standardised digital format while conducting a comprehensive set of quality checks before eventually ingesting the data into a consolidated database from where they can be made available for use.

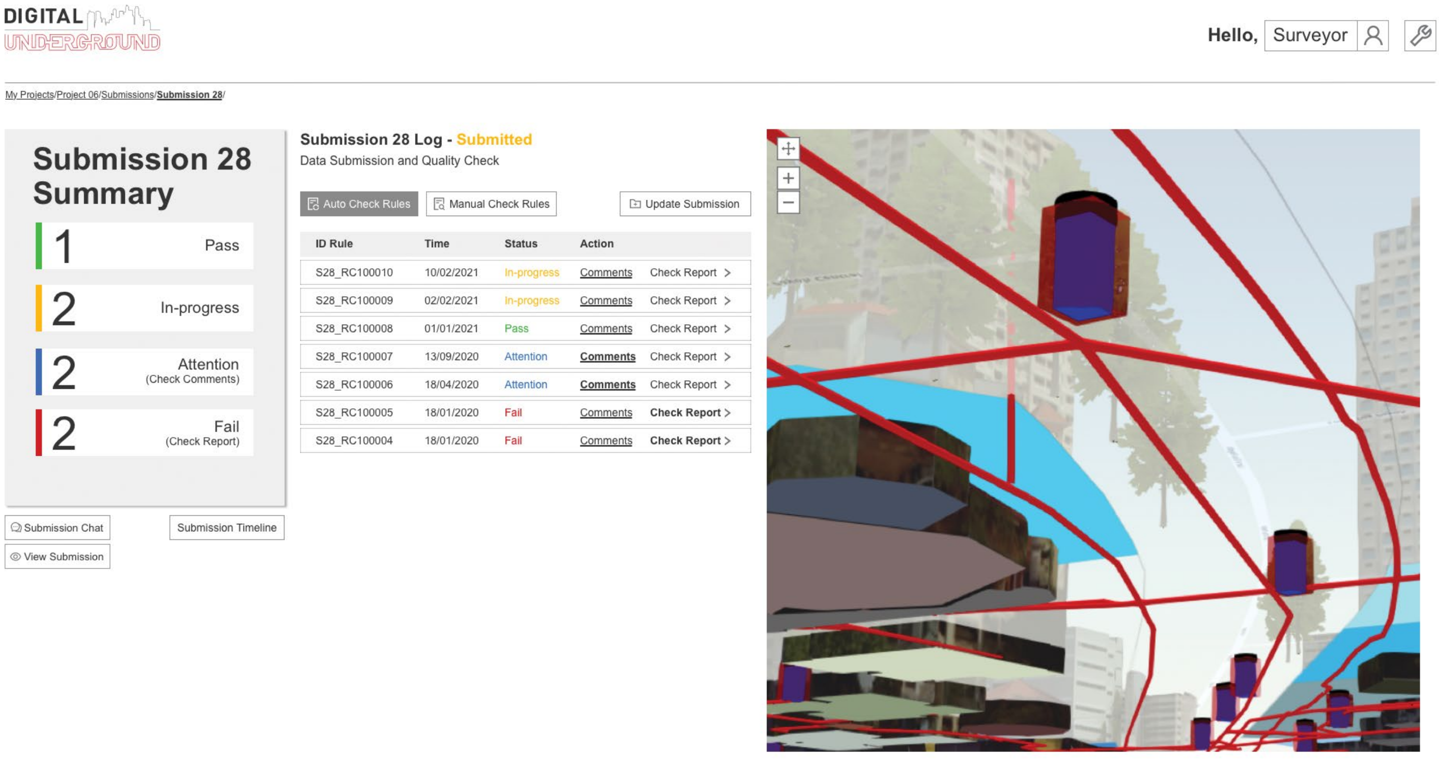
The workflow can be divided into two major parts: data submission and quality control. The former aims to guarantee that the submitted data meets minimum data quality requirements for further processing, whereas the latter further evaluates the data quality and classifies the submitted data into different quality levels before storing them in a consolidated database.

During data submission, a draft submission is created as part of a newly created or existing project. Tools are provided to convert data into the required submission format. It then goes through steps that include



uploading and validation of the data. After the data passes initial data validation, it is accepted for quality control. Quality control is composed of automated and manual (e.g., through visual inspection of the data) evaluation checks. During these steps, data is classified according to various quality levels. After this, all quality control results are reviewed before a decision is made on whether or not the submitted data is marked as acceptable.

For data validation and quality control, rules were proposed and developed to check both geometric and semantic attributes of the data. For geometric attributes, rules were developed to check the existence of duplication, to see whether coordinates of features are within a valid range or valid depth relative to the ground surface, the existence of intersections with other (existing) features, and to see if the distance between different data points is valid. For semantic attributes, rules covered the completeness of the required attribute fields, material types, dates, survey techniques and the validity of surveyor information.



Working interface of the digital platform.

Design Of A Utility Mapping Ecosystem

The demonstrated workflow offers a glimpse of a future in which all data is captured in a standardised, machine-readable format and checked to ensure data quality requirements are met. Moving into the future, processes and tools for the efficient management and documentation of quality rules are essential to manage ever-evolving data quality requirements and new data sources. Moreover, it is worthwhile to explore how the workflow can be extended to improve the assessment of locational accuracy by incorporating observation and other supporting data from surveyors and their instruments.

A consolidated database for data quality management

The role of SLA as Singapore's national mapping agency

Dr. Victor Khoo

Director, Survey and Geomatics Division,
Singapore Land Authority

The planning and implementation of infrastructure services (e.g., drainage, sewerage, gas) are currently undertaken individually by the respective infrastructure agencies and utility licensees. These implementing agencies and licensees might have to carry out extensive investigative works such as trial trenching to ascertain the exact position of existing underground utilities in order to determine if the planned alignment would be feasible or if diversion of utilities is required.

However, information on existing subterranean services and structures may not be accurate or available. At the same time, subterranean space available for utility services is becoming increasingly scarce as Singapore undergoes more intensive development both above ground and underground. As a result, the infrastructure agencies and utility licensees face significant challenges in planning for new infrastructure and the management of project timelines and costs.

As the agency responsible for survey and geomatics, the Singapore Land Authority is committed to the Digital Underground programme to progressively provide data of good quality in a timely manner for use by all the relevant stakeholders through the implementation of the Utility Survey Standard and governance frameworks, as well as the eventual setting up of the consolidated database of the nation's underground utilities. These initiatives are aimed to improve planning and construction efficiency for the infrastructure agencies and utility licensees, as well as to minimize services disruptions and inconvenience to the public.

A consolidated database for
data quality management

Conversion and integration of legacy GIS data

Ang Li Min
Wu Hao
Singapore-ETH Centre

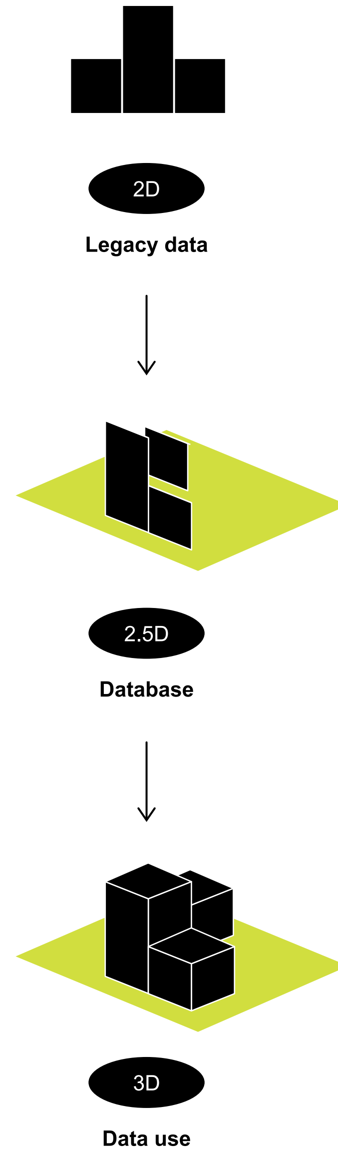
Digital Underground aims to establish a reliable digital twin of all subsurface utilities in Singapore. However, because there is no straightforward way to (re)survey all existing utility structures and produce corresponding data of the desired quality, building a nation-wide digital twin starts with utilising existing available location data, establishing a baseline for future quality improvement and reconciliation.

However, integrating these data is not without challenges. Apart from being unreliable, such records are managed in silo by the respective asset owners and come in varying representations and attribute definitions. More often than not, these records contain 2D location information, lacking information about the depth or elevation of subsurface utilities.

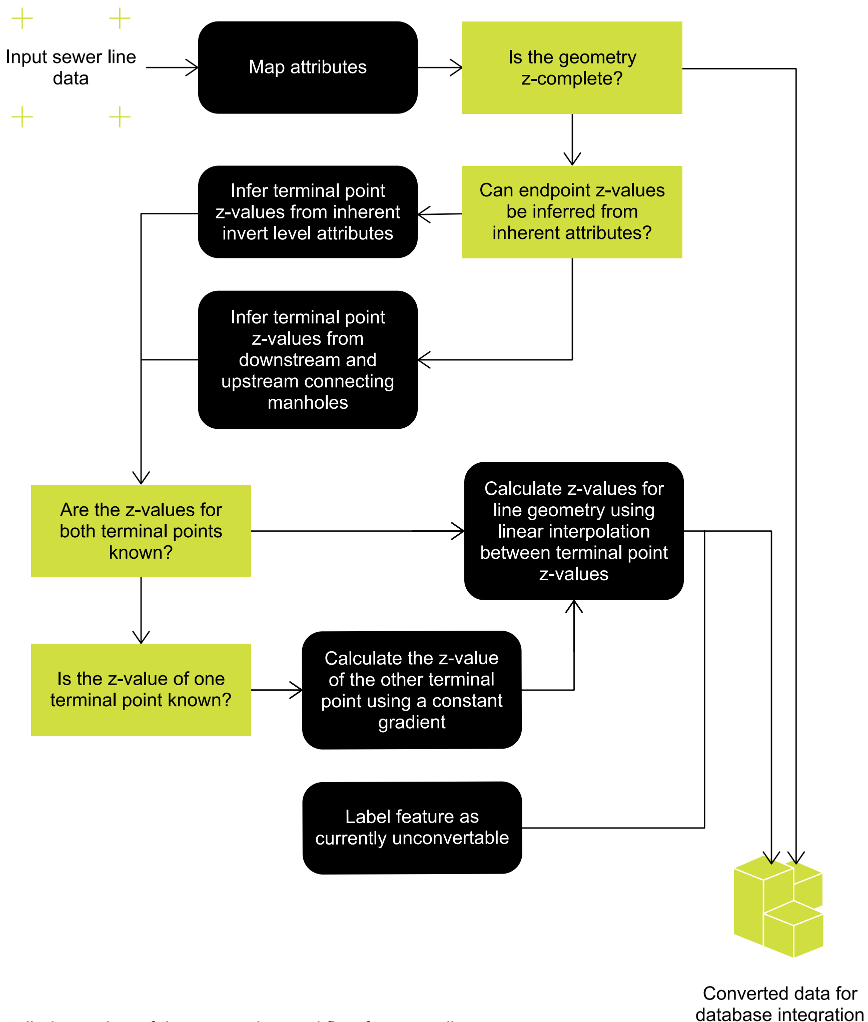
To facilitate integration of the data into a consolidated database, workflows and tools are needed that analyse and convert the data into a standard 3D geospatial representation for storage and integration with other data sources and workflows, such as for newly captured as-built data.

Comprehensive data processing pipelines were developed that transform predominantly 2D legacy GIS data into 2.5D data for ingestion into a consolidated database. To fill in the blanks for so-called ‘z-incomplete’ geometry that lacks elevation information, the following computational approaches were investigated:

- Inferring elevation values from inherent attributes and geometries, for example by calculating pipe elevation values by utilising known invert levels of connecting manholes.
- Inferring elevation values utilising heuristic rules based on utility construction guidelines or practices, for example by placing utilities at typical or advised utility laying depths below the terrain.
- Predicting elevation values through the use of an experimental machine learning approach where records that have known elevation values were used to train an algorithm that calculates values for those that don’t.

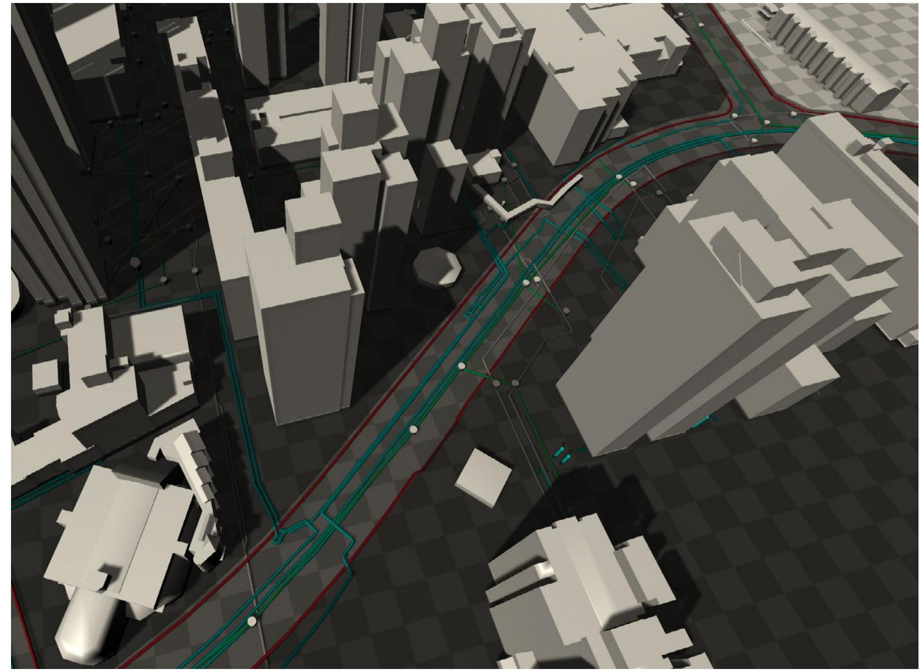


Using a case-by-case approach to select the right (combination of) conversion strategies, data conversion workflows were developed to convert legacy data and integrate them into the database. For responsible delivery and use of the data, an appropriate data quality label should be assigned because the quality of the resulting data is not guaranteed until further verification.



Detailed overview of the conversion workflow for sewer lines.

Design Of A Utility Mapping Ecosystem



Visualisation of converted data in a three-dimensional space.

Capable professionals

Instruments for developing professionals' capabilities

Dr. Jaw Siow Wei
Singapore-ETH Centre

As important as the workflows and technologies necessary to establish a reliable digital twin are the professionals that are involved in the production, management, and use of subsurface utility data.

To support capacity development for a subsurface utilities digital twin of Singapore, the Digital Underground team undertook the following research and community building activities:

- Development of recommendations for a training framework.
- Development of business models for facilities for testing, training, and education.
- Establishment of the Digital Underground Connect community of practice.

Recommendations for a competency-based training framework
To support the development of the training framework proposal, a training needs assessment was conducted first. Through an online survey, surveyors, contractors, and utility companies were engaged to define required competency levels for performing tasks throughout the geospatial data life cycle and utilising data capture techniques and asked to conduct a self-assessment to identify the gap between required and current capabilities.

From the assessment it was observed that, based on self-assessment from respondents involved in utility surveying, utility engineering, and subsurface utility data management, professionals generally observe themselves to be capable of performing their tasks in the way they are currently defined. However, respondents noted that upskilling is likely necessary to support a shift towards fully digital workflows. Another notable gap that was identified is the perceived lack of capabilities to perform non-conventional (e.g., close range remote sensing) and non-destructive surveys (using geophysics-based techniques).

The results from the training needs assessment offer a useful baseline to immediately organise training courses for professionals in Singapore. Moreover, the required competencies and proficiency levels identified by the stakeholders can be utilised to develop a competency-based framework by:

- Establishing a clear definition of roles and responsibilities of the various involved professionals.
- Creating an overview of relevant competencies based on the training needs assessment.
- Measuring the status quo: Perform an objective assessment of competency proficiency levels.
- Based on priorities (e.g., biggest needs, biggest gaps), defining the target group, learning goals, and desired outcomes for to-be-developed training and education interventions.
- Developing and delivering training and education contents in collaboration with private sector training providers.

Facility business models
Based on the results from a previous study and interviews with facility owners and operators from overseas, A small number of facility "variants" were developed. These variants were described utilising business model canvasses, describing the most important aspects of the business of setting up and operating such facilities.

Three testing facility variants were developed:

1 **Calibration facility**
A built-for-purpose facility that serves as a platform for instrument and sensor calibration, allowing users to conduct absolute calibration in a controlled environment.

2 **A space for education and research**
A space that contributes to an aware, knowledgeable, and skilled workforce, delivering capable professionals to the subsurface utility mapping ecosystem, and technological advancements.

3 **Training ground**
A facility that supports and facilitates conducting training courses for professionals in utility surveying and subsurface utility engineering.

Design Of A Utility Mapping Ecosystem

To support further development of these facilities, these variants were described using business model canvasses, a tool for describing the most important aspects of the business of setting up and operating such facilities, the required expenses, and sources of revenue. These canvasses were developed in collaboration with key stakeholders.

Business model for calibration facility

+ Key Partners

- Utility owner — for assets
- Land development agencies for regulations or mandates
- Technology providers for collaboration on the establishment of the facility
- Education institution for architectural and engineering design
- Professional bodies for calibration service certification

+ Key Activities

- Conduct instrument and sensor calibration
- Perform instrument fitness tests

+ Key Resources

- A physical space (either indoor or outdoor)
- Human resources
- Capital expenditure

+ Value Proposition

- Platform for instrument and sensor calibration
- Can ensure data quality and reliability

+ Cost Structure

- Initial capital costs to set up the facility
- Regular expenses for daily operation

+ Customer Relationships

- Involvement of stakeholders and experts for design and participation in advisory board

+ Customer Segments

- Private practitioners
- Stakeholders from utility industry

+ Revenue Streams

- Service charges for instrument calibration
- Fees for use of the facility
- Lending, leasing and rental fees

+ Channels

- Construction work contracts
- Requirements, standards and regulations for instrument calibration
- Regular consultation and discussion with SISV
- Tender or contract briefing

Aerial image of the Q-Leak facility of the Water Supplies Department of the HKSAR Government for training, research, and education, designed by the Hong Kong PolyU Department of Land Surveying and Geo-Informatics. The centre covers about 2 400 square metres with facilities simulating the complicated water supply network of Hong Kong and underground water main leakage under various conditions and scenarios, including different pipe sizes and materials, as well as various water flow patterns. The centre provides a safe environment for leak detection practitioners to conduct training and skills assessments on various leak detection technologies.

Image:
Hong Kong PolyU, HKSAR Government Water Supplies Department

Hexagon Detection Training School in Whitchurch, United Kingdom. The purpose-built facility replicates street and construction site environments to give trainees ‘real’ world experience.

Image:
Leica Geosystems

Capable professionals

Digital Underground Connect: Joint learning in a Community of Practice

Open engagement with and between various involved stakeholders is essential for the development of robust practices and capabilities for reliable subsurface utility data. Digital Underground Connect is a Community of Practice established to serve those needs and advance the state of knowledge and practices in Singapore.

DUConnect: LEARN

Community engagement for better data and practices
Capable professionals are essential for the production and delivery of reliable data on subsurface utilities. In 2019, SEC and SLA teamed up with Bentley Digital Advancement Academies and the Singapore Institute of Surveyors and Valuers to establish Digital Underground Connect (DUConnect).

DUConnect is a Community of Practice that aims to contribute to reliable underground information, processes and strategies by creating an open platform where professionals come together to share, exchange and advance their knowledge and improve their skills and practices on the topic of underground digital twins.

Meet. Learn. Improve.
A total of seven events were organised thus far, focusing on different aspects of underground digital twins and subsurface utility data, with an increasing number of participants from Singapore and overseas. Each event was designed to consist of three core building blocks:

- **Meet** – a safe space is provided to stakeholders across domains to interact, socialise, and share their experiences.
- **Learn** – speakers from Singapore and overseas are invited to share their experiences and innovations.
- **Improve** – participants engage with each other in a workshop setting to discuss solutions for pressing challenges.

As a key principle, all lessons and insights were captured and documented as a continuously growing knowledge base on the topic of underground digital twins.

“It is reassuring that the community is involved in moving subsurface utility surveying and mapping forward, rather than relying purely on legislation.”

“I appreciate the constant sharing via webinars. I hope that knowledge sharing shall continue so that more can be learned from others.”

“Hey, I got to attend a seminar in Singapore ... while at home! For free. How can it get better?”

“One of the better organised webinars I have attended this year. Well done!”

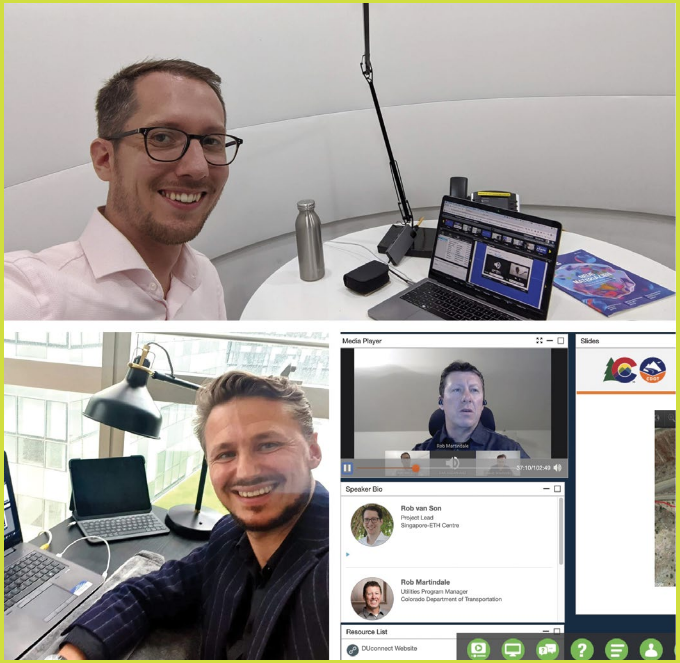
The Community of Practice as a persistent infrastructure for community involvement
With the establishment of a Community of Practice, the project has established an essential infrastructure for the further development, review, and improvement of Singapore’s utility mapping ecosystem. The existing basis can be utilised for continued sharing of experiences, knowledge base development, the development of guidelines and best practices in dedicated workshop sessions.

- Themes and challenges to address
- Data capture for a reliable digital twin of subsurface utilities
- Digital twins to support future underground construction
- Digital workflows for data collection and management*
- Subsurface utility data sharing*
- Unlocking the value of digital ground information*
- Improving the quality of subsurface utility information*

* organised as a virtual event due to Covid-19 restrictions

DUConnect: Improve

DUConnect: The first virtual-only session



Capable professionals

User experience: The make-or-break of going digital

Jakub Wachocki
Director
Success Advisory
Bentley Systems

Industries around the world are being disrupted one after another, from banking to logistics to construction, but one single concept is at the centre of such transformation — the user experience (UX), which is the way that the users interact with the new digitally-enabled workflows and extract value from such interactions. However, who is the 'user' in the context of the city infrastructure? Anyone who interacts with the city's assets, above or below ground, is becoming increasingly accustomed to leveraging new digital experiences such as social media or mobile. Data flows constantly, seamlessly and is available 24/7.

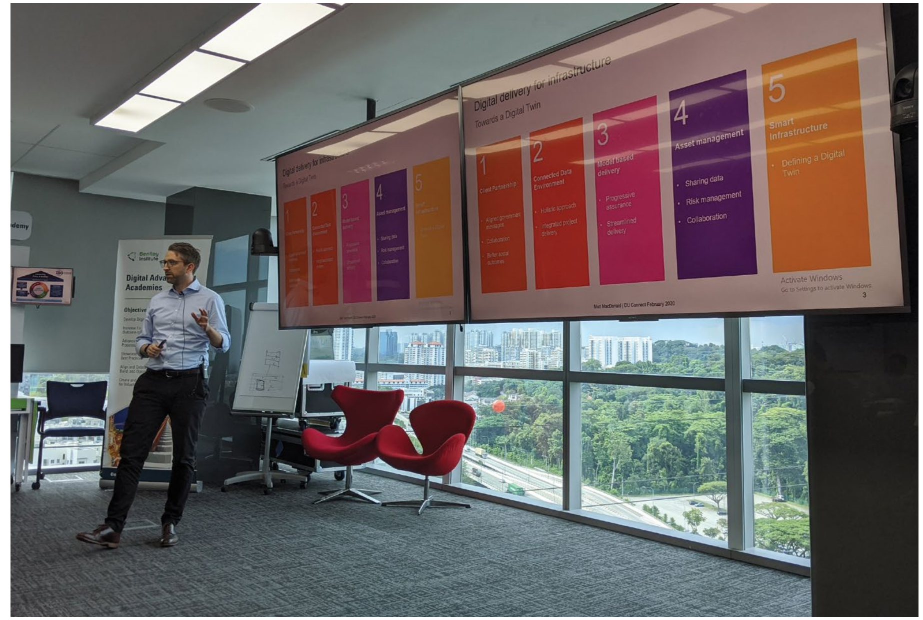
In the context of the underground assets, our industry is used to cumbersome processes, outdated data, inaccuracy, mistrust, and contractual hurdles standing in the way of achieving the desired business outcomes. Surveyors, construction managers, suppliers and asset managers are no longer happy with the status quo. They aim to leverage digital assets such as the digital twin and platform technologies such as Connected Data Environments to capture, validate, assure, review, control, distribute and access data when required.

At the same time, a new capital project delivery model is being adopted due to accelerated pandemic related needs — the global work-sharing. Organisations worldwide can now contribute to creating digital assets and leveraging the already created ones in their digital workflows regardless of the physical location of the physical assets in question. Singapore's highly skilled workforce can therefore leverage its world-class talent in Singapore and the surrounding regions whilst contributing to the economic prosperity of the city-state.

Brainstorm during DUConnect #2

Communities and initiatives such as the Digital Underground project and the DUConnect community of practice play a pivotal role in ensuring that these new digital workflows come to life, are relevant to the industry, address the most pressing challenges, and create business opportunities. DU helps translate the needs of the stakeholders involved in underground assets into a set of functional requirements for Singapore's soon-to-come subterranean digital twin. At Bentley, we understand how vital it is to identify, prioritise and deliver the new organization-based, persona-based and workflow-based outcomes through a well-designed and success-oriented digital advancement strategy. We are looking forward to continuing our support and help ensure the viability and sustainability of these new value-adding experiences.

DUConnect group photo taken after the first session, hosted at Bentley Systems' premises



DUConnect group photo taken after the first session, hosted at Bentley Systems' premises

Reflections

Digital Underground: A unique approach to mapping underground utilities

A number of jurisdictions around the world have recognized the human and economic cost of unreliable location and other data about underground infrastructure and have undertaken initiatives to address this problem. Among them, Singapore recognized the urgency for a map of its underground utilities for a number of purposes; planning, design, construction, ownership and maintenance of underground infrastructure.

Whereas other jurisdictions have implemented partial solutions in the form of one call centres, legislation mandating the submission of accurate as-builts, and other measures with varying degrees of success, Singapore has recognized that whereas partial measures may provide some business benefits, they do not resolve the primary problems resulting from inaccurate, outdated and incomplete maps of underground infrastructure.

Instead Singapore has taken a holistic approach to the problem of mapping underground infrastructure at a national and city level. Over the past four years, the Digital Underground project has investigated the foundations of an ecosystem that supports and enables a reliable map of subsurface utilities covering a wide array of themes such as governance, legislation, capacity development, data capture standards, quality control and consolidation of 3D utility information for a wide variety of use cases including planning and land administration applications and others.

Because of the approach that Singapore has adopted and the fact that the Digital Underground project has actively engaged the international community, many international jurisdictions are watching closely as Singapore moves into the implementation phase. The approach developed by Singapore could become a widely adopted model for addressing the challenge of developing a reliable map of underground infrastructure at the city, region, or national level.

Reflections

Dr. Geoff Zeiss

Dr Geoff Zeiss tracks the contribution of geospatial technology to the digitalization of the construction and energy industries on his Between The Poles blog and other media. His area of special focus is locating, mapping and sharing information about underground utility infrastructure. A white paper “Reducing Damage to Underground Utility Infrastructure During Excavation” prepared by Geoff and Dr. Sakura Shinoaki was recently released by GITA. Geoff is advisor to the Digital Underground project.

Growing an underground digital twin from sparse information

Time is money. Space as well. Urbanization allows using both efficiently if the infrastructure is well planned, implemented, maintained, and used. All these steps need accessible geospatial information of well-defined quality. Reality capture i.e., providing this information, is a core contribution of geomatics. While it is still challenging at large scale above ground, the necessary steps are known. The technology in terms of spaceborne, airborne and terrestrial mapping sensors as well as the software for data processing, and 3D modeling is available, and the data capture can be carried out at almost any time. If above ground geospatial information is missing, it is just a matter of time and money to get it through reality capture.

This is entirely different for the underground. No technology allows mapping the underground in a similarly versatile and easy way. And this is not because such technology was just not needed in the past. It is due to physical restrictions. As soon as the pit is closed optical and tactile methods for surveying are not applicable anymore. Capturing underground utilities, infrastructure or spaces is very difficult then and typically comes with an unfavorable tradeoff between spatial resolution and ground penetration depth.

Therefore, creating and maintaining a digital twin of the underground requires a highly interdisciplinary approach. It necessarily relies on the integration of all available data e.g., from spatially and temporally sparse open-pit surveys, geophysical exploration, and prior knowledge from construction plans to clues derived from surface infrastructure. In the long term, legal and contractual obligations as well as sensible workflows may allow the underground digital twin to grow from a set of sparse data of varying quality into a complete and consistent high-quality representation. In the short- to mid-term, the stakeholders must be willing to invest in this gradual growth, and the users must be aware of gaps and uncertainties.

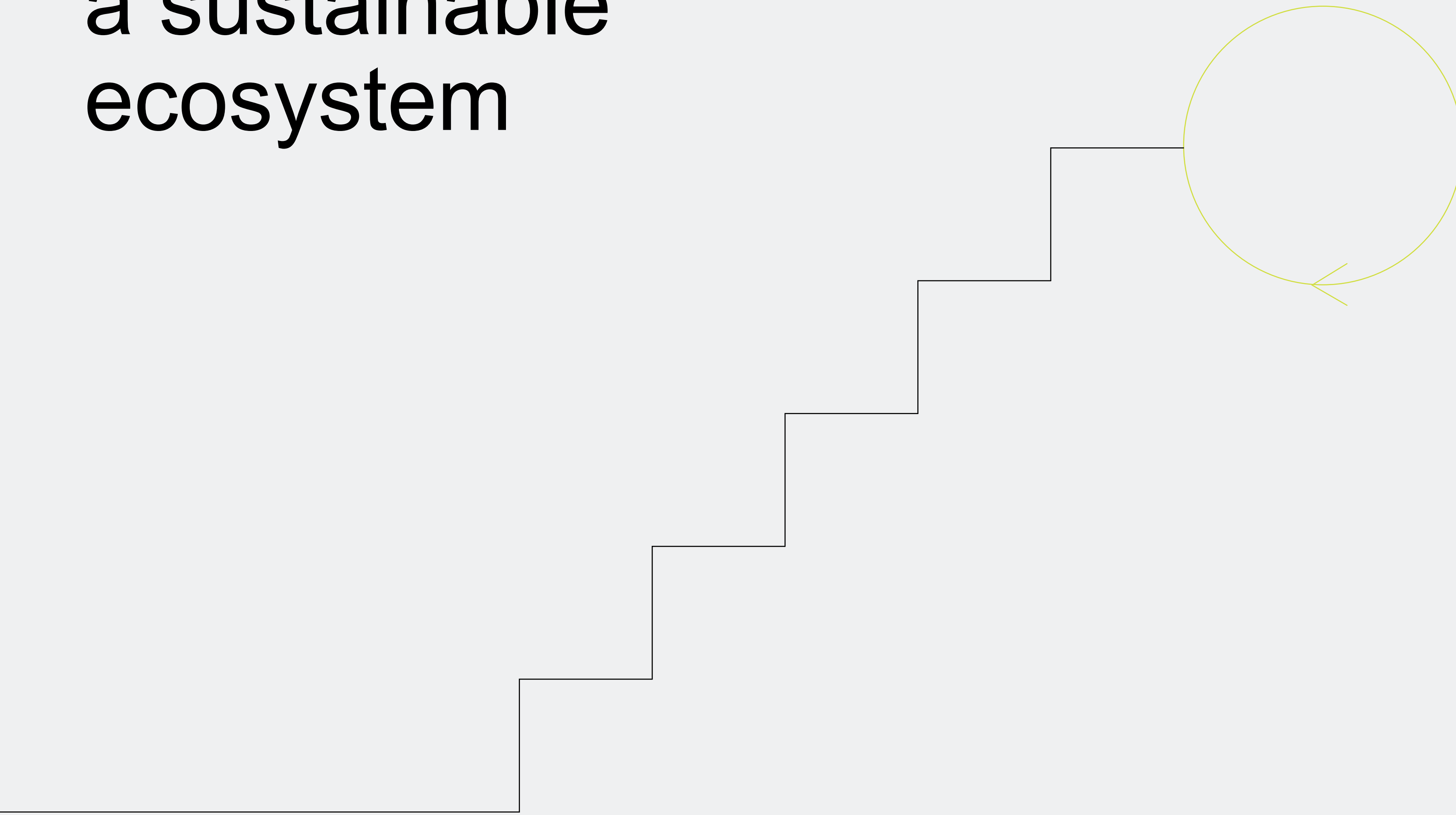
It is exciting to see that Singapore embarked on this journey with the Digital Underground project. The logical next step should be the practical exploration in a variety of real-world study cases with partners from various industries and agencies. This will help demonstrate how reliable data can be captured, stored, improved, and made available for the benefit of users involved in the planning, construction, maintenance, and operation of underground facilities and space. In the long term this will help Singapore save space, time and money.

Prof. Dr. Andreas Wieser
Professor of Geosensors and Engineering Geodesy, ETH Zürich

Andreas Wieser is a professor of Geosensors and Engineering Geodesy at ETH Zürich primarily working on the development, calibration and optimization of geodetic sensor systems as well as parameter estimation and quality control for monitoring of structures and surfaces, and for digitization of reality. He is a Co-Principal Investigator of the Digital Underground project.

Future steps towards a sustainable ecosystem

Moving forward, the recommendations delivered by the Digital Underground project need to be put in practice, tested, evaluated, and continuously improved. It is vital that this is done together with all involved and impacted stakeholders.



A living lab for mapping the underground

Phase 2 of the Digital Underground project has yielded a range of recommendations for the further development and establishment of a utility mapping ecosystem. Now is the time to put these recommendations into practice. Continuous monitoring and improvement will remain an essential part of a sustainable utility mapping ecosystem in Singapore.

After over four years, the first two phases of Digital Underground have delivered increasingly detailed and comprehensive recommendations towards a reliable digital twin of subsurface utilities in Singapore. Extensive analysis of overseas practices and the engagement of numerous stakeholders have contributed to a “design” of a utility mapping ecosystem that we believe is both necessary and achievable.

It is now time to take the next step and put these recommendations into practice. We are certain that putting matters into action will teach us new lessons and necessitate refinement and improvement of data governance, surveying practices, and more. We therefore highly recommend to introduce changes gradually and to establish pilot projects as part of Digital Underground Phase 3 to assess the effectiveness, feasibility, and viability of these changes. The community of practice that was established by the project will continue to serve as leverage to involve public and private sector stakeholders, facilitate on-boarding, and gather feedback.

Developing a reliable digital twin is a long-term effort that needs to be sustained. And good data governance is evidence-driven and emphasises continuous improvement. It is therefore vital that the necessary infrastructures and instruments are in place to monitor the performance of the ecosystem, evaluate existing practices, deploy exciting new mapping technologies, and incorporate feedback from participants and users moving into the future.

For the long term, Singapore has the potential to become a world-leading living lab for mapping the underground and set an example for other jurisdictions to emulate. Driven by an ever-increasing need to go underground and supported by capable and supportive organisations and professionals, all necessary ingredients are in place.

Collaboration as a means and an end

The Digital Underground project has delivered its results through research and collaboration.

Not only is collaboration valuable as a means in order to develop recommendations that are well-supported. It is also a critical component of a sustainable utility mapping ecosystem moving into the future and requires conscious effort.

Future steps towards a sustainable ecosystem

Collaboration with government agencies, utility companies, contractors, surveyors, and solution providers has been invaluable to our research. It has helped us develop grounded recommendations based on the experiences and insights from various stakeholders involved in the business of mapping subsurface utilities. It has also given us access to numerous opportunities to capture data and evaluate new techniques hands-on. And on the global stage, we are seeing a growing network of jurisdictions that face similar challenges as Singapore and an open exchange of ideas and solutions.

Moving into the future, collaboration with stakeholders from various domains is essential to develop workflows and solutions that are feasible and viable. Through pilot-based research, real-world projects need to be utilised to try out new workflows and technologies, in collaboration with and by the intended end users. Collaboration with surveyors, contractors, asset owners, regulators, end users, and many more will be crucial in the third phase of Digital Underground.

Not only is collaboration necessary for further research and development. It is also a goal on its own that forms the basis of an ecosystem that is sustainable in the long run. After all, solving problems alone or in silo should never be the easiest or most desirable approach. We have experienced first-hand that collaboration, when done well, improves relationships, communication, and awareness between stakeholders and can minimise redundancies, leading to solutions that can be applied generally. Through collaboration, professionals are able to increase their efficiency and productivity, complementing each other, especially in situations such as the one we find ourselves in where capacity and other resources are already scarce.

The lack of reliable information is something that affects everyone and needs to be addressed through a comprehensive, whole ecosystem approach. We have experienced first-hand how open interaction and collaboration with stakeholders leads to better results and we heartily encourage a conscious effort to ensure future efforts continue in the same spirit.

Surveyors, solution providers, government representatives, and researchers during technology trials

Closing Words

Dr. Victor Khoo
Director, Survey and Geomatics Division,
Singapore Land Authority

In Singapore, almost all utility assets are buried underground in order to free up valuable above ground space for other usage. These underground assets which consist of power cables, gas pipes, telecommunications lines, water pipes and wastewater networks are critical infrastructure that keep the city functioning just like the internal organs of the human body.

Every day, we dig up the streets to place new pipes, conduct inspections, and maintain and repair existing network lines. Sometimes, the same street is dug up repeatedly in a short interval of time, causing inconvenience to the general public. Largely, this is due to a lack of accurate and reliable underground utility maps. To facilitate better management of underground assets and space, a better map is required.

To address the issue, Digital Underground (DU) was initiated by Singapore Land Authority (SLA) in collaboration with the City of Zürich and the Singapore ETH Centre (SEC) in 2017. The initiative aims to develop a sustainable ecosystem for capturing reliable and accurate 3D locations of underground utilities. In the first phase of the research project, the team developed a road map and strategies for development.

A Utility Survey Standard was also established to support the industry and agencies in Singapore. In the second phase, the research team sought to develop a prototype system, data governance as well as conduct a study into requirements for training.

With the second phase of Digital Underground completed, we have reached an important milestone in the initiative before we move into the third phase to pilot the new end-to-end submission workflow. SLA is working closely with the Ministry of National Development to put in place the necessary governance, workflow and submission framework based on the recommendations from the Digital Underground project.

The key success factor will be stakeholder engagement, especially with private sector asset owners. The benefits of the initiative need to be clearly defined and articulated. The path needs to be charted and will take many years. I am glad that we have started this journey and to bring many new passengers on board on the way to our destination.

Team

Principal Investigators

Prof. em. Dr. Gerhard Schmitt
Principal Investigator
Singapore-ETH Centre

Prof. Dr. Andreas Wieser
Co-principal Investigator
ETH Zürich, Institute of Geodesy and Photogrammetry

Advisors

Dr. Gerhard Schrotter
Director, Geomatics and Surveying
City of Zürich

Dr. Geoff Zeiss
Principal
Between The Poles

Singapore-ETH Centre

Rob van Son
Project Lead

Dr. Jaw Siow Wei
Postdoc Researcher
Data Capture

Dr. Yan Jingya
Postdoc Researcher
Data Modeling

Wu Hao
Lead Software Engineer

Dr. Miao Yufan
Software Engineer

Ang Li Min
Research Assistant

Thomas Oeberseder
Technical Specialist

Michelle Chan Mei Har
UX/UI Specialist

Isaac Lu
Visualisation Developer

Hilal Fitri bin Rohaidi
Visualisation Developer

Singapore Land Authority

Dr. Victor Khoo
Director, Survey and Geomatics

Soon Kean Huat
Senior Principal Surveyor

Wu Defu
Principal Surveyor

Richard Loo
Senior Surveyor

Sandy Teo
Senior Surveyor

Woo Mun Shih
Technical Manager

Ng Chun Tian
Senior Manager

Design and layout
Roots

Editing
Michelle Chan Mei Har
Rob van Son

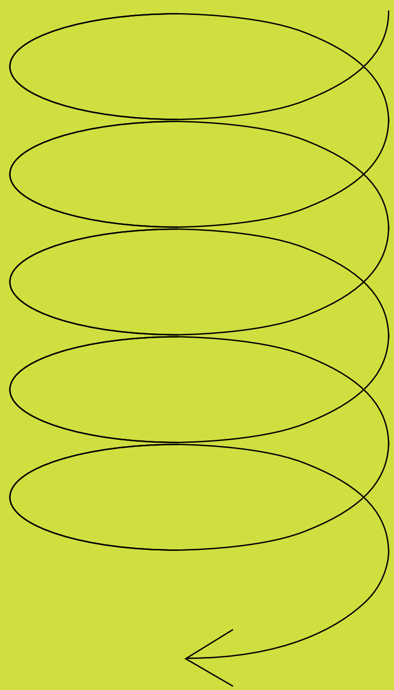
Contributions
Ang Li Min
Michelle Chan Mei Har
Hilal Fitri bin Rohaidi
Dr. Jaw Siow Wei
Dr. Victor Khoo
Isaac Lu
Mak Weng Tat
Dr. Miao Yufan
Prof. em. Dr. Gerhard Schmitt
Shane Shi
Tan Boon Huat
Jimmy Tan
Rob van Son
Matthias Vollmer
Jakub Wachocki
Prof. Dr. Andreas Wieser
Dr. Yan Jingya
Dr. Geoff Zeiss

Published by Singapore-ETH Centre

ETH Singapore SEC Ltd (UEN 201016935D)
1 Create Way
CREATE Tower #06-01
Singapore 138602

Printed in Singapore

This publication is produced by the Digital Underground project at the Singapore-ETH Centre, which was established by ETH-Zurich and the National Research Foundation Singapore (NRF), under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. 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 the Singapore Land Authority.



The Digital Underground project is a collaboration between Singapore Land Authority and the Singapore-ETH Centre towards a reliable digital twin of subsurface utilities for planning, land administration, and construction in Singapore.

Following the release of a roadmap upon conclusion of phase 1 of the project in 2019, SLA and SEC commenced the second phase of the Digital Underground project called "Foundations of a sustainable utility mapping ecosystem". Phase 2 aims to translate the roadmap into a concrete design of the processes and supporting instruments that are needed to realise the desired ecosystem and produce and deliver accurate, up to date, and complete digital data to planners, land administrators, and developers.

This booklet presents an overview and summary of the activities undertaken by the project team throughout phase 2 of the Digital Underground project, the results that were developed, and the ambitions and achievements from various stakeholders and supporters that are an integral part of the ecosystem.

sec.ethz.ch | digitalunderground.sg | duconnect.org