Success Factors for a Digital Twin of Subsurface Utilities - Experiences from the Comparison of Singapore and Zurich

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SUMMARY

Above-ground space is scarce in many cities and must therefore be used optimally. A frequently used possibility for this is the relocation of utilities and other infrastructures, e.g., roadways to the underground. Reliable information about underground utilities can help planners, land managers, facility owners and other stakeholders make better informed decisions and streamline work processes. However, in many cities, underground infrastructures are not documented in sufficient quality or are not accessible to all stakeholders.

In the city of Zurich, the utility cadastre was initialised in 2001. As a result, digital data has been available in a uniform format and in a defined structure across all asset types for almost 20 years. The utility operators guarantee the timeliness and accuracy of the data, so that many applications can be undertaken based on the data of the utility cadastre without additional investigations.

In the highly densified city of Singapore, using the underground space efficiently and thus gaining high-quality above-ground space is particularly important. A unified data basis in terms of a digital representation of the underground, though, is not yet available. In 2017, the Singapore Land Authority has thus initiated a project "Digital Underground" in collaboration with the Singapore-ETH Centre, and initially also Geomatik + Vermessung Stadt Zürich, to analyse technologies and challenges, demonstrate tools, and develop workflows for the creation of a digital twin of subsurface infrastructures. During the project, it became clear that the technical challenges are manageable but are likely not the main, or at least not the only, success factors for the development and long-term operation of a digital twin of subsurface utilities.

This paper presents the elements for a successful implementation of a joint digital twin of all subsurface utilities, based on the experiences from the city of Zurich and the "Digital Underground" project.

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1 INTRODUCTION

Most cities and urban centres around the world have grown rapidly in recent decades. According to the World Bank[1], the urban population currently comprises 4.4 billion people and will reach 6.3 billion by 2050. As above-ground space is limited, it must be used optimally, i.e., for the most valuable needs associated with this growth. The trend in planning processes in recent years has therefore been to utilise the underground much more. Above-ground space should be prioritised for permanently inhabited or used areas. Conversely, this means that utilities and other infrastructure, e.g., roads or storage spaces, are being shifted to the underground. These developments can be seen, for example, in Singapore[2] and in the city of Zurich[3].

Reliable information on underground structures and utilities is an essential prerequisite for the planning and design of new facilities. Even if, in some cases, the future infrastructure is built deeply underground (see for example the Deep Tunnel Sewerage System[4] in Singapore, there is always a need for interfaces to the infrastructure built at or above ground. Such interfaces should be easily accessible for maintenance and operation. Since transport and supply infrastructures are also a public task, the areas of public property and in particular the current road network are the main priority for these structures. Consequently, information on the use of the underground is required from the surface down to the depth of the bottom-most installations and engineered spaces.

However, in many cities, underground infrastructures are not documented in sufficient quality or are not accessible to all stakeholders. As a result, many construction projects require substantial effort for investigating and documenting the initial situation. Often, so-called trial trenches have to be excavated for this purpose to expose conduits and pipes and thus facilitate documentation of occupied and available space.

In the two cities of Singapore and Zurich, the documentation of underground utilities has so far been very different. We illustrate this by means of a comparison. Based on the historical development and current state in Zurich as well as on the joint research project "Digital Underground" by the Singapore Land Authority and the Singapore-ETH Centre, initiated with

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[1] https://www.worldbank.org/en/topic/urbandevelopment/overview
[2] https://nextcity.org/urbanist-news/underground-city-movement-singapore-helskini
[3] https://www.urban-transport-magazine.com/en/zurich-expands-its-public-transport-network-significantly-the-strategy-for-2040-has-been-approved/
[4] https://www.pub.gov.sg/Professionals/Requirements/Used-Water/DTSS

inputs from Geomatics + Surveying City of Zurich, it is shown how the development of a digital twin of the underground can be successfully approached.

2 SITUATION IN ZURICH

2.1 Historical development

The digitisation of utility data started in Zurich (as in most parts of Switzerland) at the beginning of the 1990s, in parallel to the digitisation of the property cadastre. However, the tradition of mapping utility assets at a scale of 1:250 (urban areas), 1:500 (rural areas) or 1:2000 (mostly regional utilities) goes back to the Fifties when a period of intense construction activity began. Since then, many asset owners have long-established processes to ensure that newly constructed assets are surveyed in the open trench and then documented in the comprehensive utility cadastre (as part of their digital twin).

In the city of Zurich, a joint digital cadastre of all underground utilities was launched in 2001. The initiative for this data set came from the various asset owners. However, the concept of joint documentation of the occupied underground spaces goes back further into the analogue age. Various developments in digitalisation have simplified the development of the digital underground cadastre:

- With the reform project on the digitalisation and further development of the property cadastre into a multi-purpose cadastre from the mid-1990s onwards, more and more suitable situational data was available for all spatial data sets (Steudler, 2015).
- The methods used at the time for updating individual utility maps was based on simple location determination of conduits and pipes in relation to prominent objects (distance measurements to building corners, kerbside etc). The introduction of common situational (or reference) data in digital format (i.e., objects with numerical coordinates) resulted in an improvement in location accuracy between the individual cadastral themes.
- The above-mentioned reform also established the concepts of harmonised data models and a standardised exchange format in Switzerland (Keller et. al. 1999). Based on these two principles, the exchange of data between the comprehensive pipeline cadastre in the various GIS applications and the common pipeline cadastre could be realised.

The individual utilities for supply and disposal (sewerage, water, gas, electricity, district heating, communication) are built and operated very differently. At the same time, the desired application capability of the underground utility cadastre, namely simple retrieval of information about the use/availability of space, had to be supported. This was achieved by agreeing on basic geometries (nodes as points, edges as lines and special constructions as surfaces) and on a few properties such as asset type, dimensions of the conduit and essential functions (e.g., manhole, cabinet or valve) to be represented in the database.

Each asset owner then had to develop an export interface to the common data model based on their internal database schema and output the data periodically. At Geomatik + Vermessung, the municipal service department for the operation of entire spatial data infrastructure, the individual data deliveries were imported and merged into a complete data set. This central data set is kept up to date with regular deliveries.

This means that the latest data from all asset owners is available when planning conduits. The data can also be used for excavation during regular construction work as well as when uncovering a section in an emergency case (e.g., in the event of a burst water pipe), meaning that very little manual labour is required to locate conduits and pipes before starting the on-site work (see also Figure 1).

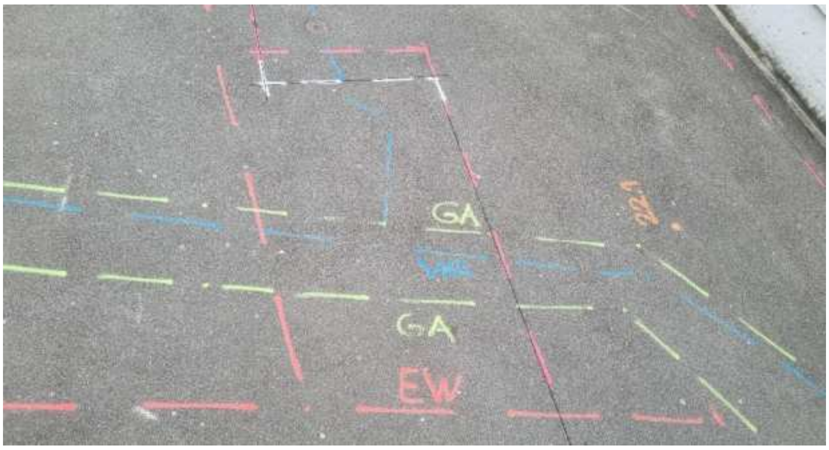

Figure 1 Visualisation of the utility conduits and pipes for excavation work based on the underground cadastre (coloured by asset type)

In order for the joint utility cadastre to function successfully, a number of principles must be agreed and adhered to:

- Decentralized data maintenance and centralized access: The data is regularly updated by each asset owner and delivered to the central system.
- Each asset owner is responsible for ensuring that their data is up-to-date and correct.
- Construction sites for which no currently valid statements can be made about the course of the pipeline are marked as perimeters in the data.
- The data is made available (to a certain extent) to all entities that also provided data for the central database. Additionally, public agencies needing the data have access and under special restrictions entities entrusted by these agencies or the previous data providers. Private persons also have access to the information so that, for example, the development of a property can be planned more easily. Access to the data is subject to only minimal restrictions.
- Any discrepancies between the data and reality, noticed during data acquisition, planning, or construction are reported in order to improve the data quality.

As a result, digital data has been available in a uniform format and in a defined structure across all asset types for almost 20 years. The utility operators guarantee the timeliness and accuracy of the data, so that many applications can be undertaken based on the data of the utility cadastre without additional investigations.

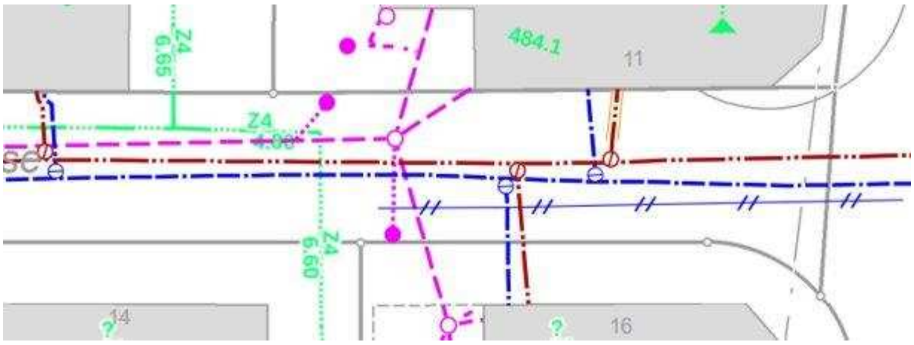

Figure 2 An extract of the combined utility cadastre in Zurich (coloured by asset type)

2.2 Legal basis

One of the decisive success factors for a functioning utility cadastre is the legal basis, which has obliged private energy and communication providers across entire Switzerland since 1994 to record the location and type of installation of their cable lines. Upon request, the owners shall also be able to provide this information to authorised persons.

The two responsible agencies for water supply and wastewater disposal in Zurich are also obliged by federal law to document their infrastructure and pipelines. The basis for the water agency is securing the supply according to the federal act on National Economic Supply. The municipalities are responsible for general planning so that the security of supply of drinking water, process water and fire-fighting water for all buildings and irrigation water for agricultural land can also be guaranteed in the medium term. Without knowledge of the existing network infrastructure, this planning cannot be carried out with the required quality.

In the area of sewerage, the legal basis comes from environmental protection legislation. Among other things, the municipalities must be able to demonstrate that the wastewater is correctly discharged into the sewage treatment plants. Knowledge of the network infrastructure is also essential for this.

The geoinformation legislation, which came into force in 2008, provides a framework lfor the technical harmonisation of spatial data. This allows for a simplified exchange among the various actors. The high level of responsibility of the pipeline owners for the documentation of the structures is also reflected in the ordinance on utilities cadastre of the canton of Zurich, which states in its § 10:

> [1] *The asset owners are obliged to have new utilities surveyed before the trenches are backfilled.*
> [2] *If existing pipelines with an imprecise location or utilities not yet included in the utility cadastre are exposed, they must be measured.*
> [3] *If new or exposed utilities are covered before they are surveyed, they must be exposed at the expense of the asset owners to such an extent that they can be properly surveyed.*

The legal obligation for utility owners to document the location and route of their conduits has led to the surveying of new conduits in open trenches becoming very well established. This also simplifies the supplementary data collection for the creation of a digital twin. The utility cadastre has become an indispensable tool not only for the asset owners but also for many other organisations.

3 SITUATION IN SINGAPORE

3.1 Legal base and current situation

In the highly densified city of Singapore, using the underground space efficiently and thus gaining high-quality above-ground space is particularly important. A unified data basis in terms of a digital representation of the underground, though, is not yet available. Currently, there exists only a regulation on how to survey newly built utility infrastructure, but there is no requirement for the registration and proper documentation of the entire infrastructure by the asset owners, for example in a geographic information system (utility cadastre). The data are kept exclusively by the asset owners and are only made available to third parties upon request, for small sections at a time and on a paid basis.

Neither the owners of the assets nor the users can make a reliable statement about the current quality of the data, but stakeholders interviewed within the Digital Underground project reported that it is obvious from many inconsistencies between situations in trial trenches and existing plans or data bases of the asset owners that the information cannot be trusted. Especially in connection with earthworks, this situation is unsatisfactory. The consequence of this situation is that for each excavation and construction project, investigations must be made into the presence, location and extent of all assets in the project perimeter. The legal regime places the responsibility for the integrity of the assets on the construction companies and the asset owners are not obliged to provide accurate information on the location and extent of their assets. According to the talks with various users in the elaboration of this paper, the arrangements take place according to the following pattern:

- (Chargeable) acquisition of the plans from all asset owners for the project perimeter.
- Coarse planning of the alignment of the new utility on the basis of the documents received.
- Acquisition of permits and licenses from relevant authorities for approval to carry out excavations.
- Excavation of trial trenches to validate the location of all assets. In addition to trial trenching, non-destructive measurement methods (electro-magnetic locating, ground penetrating radar) are used to determine or verify the position of utilities.
- If expected pipes or conducts are not found, further trial trenches have to be excavated to actually locate them, even if they may be outside the project perimeter.
- In the case of new construction over a longer distance, the trial trenches may not allow the intended alignment to be followed and therefore a new alignment may be necessary, possibly even in other streets, resulting in further trial trenches.
- Design of the new alignment based on the available underground space (with different minimum distances depending on the asset).
- Approval by various authorities. If the alignment is not approved, several steps may have to be repeated.

- Execution of the construction project and preparation of the as-built documentation in the open trench. If the time between planning and execution or the time needed for the execution are long, trial trenches may need to be excavated again to confirm the presence and location of available space and underground infrastructure assets.

Due to the lack of standards for the documentation of trial trenches the same procedure will be used again and again if different construction projects are carried out within the same perimeter over time. Based on the cost provided by construction companies for a single trial trench and estimates of the number of trial trenches open daily we estimate the cost of these trenches alone at S$75 million per year. If, on the other hand, reliable data are available on the subsurface infrastructures, the process can be massively simplified, shortened, and the costs of related construction projects will be reduced significantly.

3.2 Project Digital Underground

To overcome this situation, the Singapore Land Authority has initiated the project Digital Underground (see sec. 1), in 2017. The goal was to analyse technologies and challenges, demonstrate tools, and develop workflows for the creation of a digital twin of subsurface infrastructures (Yan et. al. 2018, Van Son et. al. 2019).

In several project phases, the technical prerequisites for a data flow between field surveys, the joint digital twin of the entire subsurface utilities and the specialist twins of the individual system operators were established. These workflows were implemented in a pilot application and tested using various construction projects. Different measurement methods were also used to find out which workflow for data collection and data maintenance best corresponds to today's construction processes.

Based on the findings of the project as well as further input from stakeholders, a digital twin of subsurface infrastructures is widely requested. Many stakeholders would like easy access to high quality data as part of the digitalisation of construction. As long as these are lacking, high costs are incurred for the construction of trial trenches to locate the pipes and conducts, see sec. 3.1.

During the project, it became clear that the technical challenges are manageable but are likely not the main, or at least not the only, success factors for the development and long-term operation of a digital twin of subsurface utilities.

Figure 3 Coloured point cloud of a trial trench

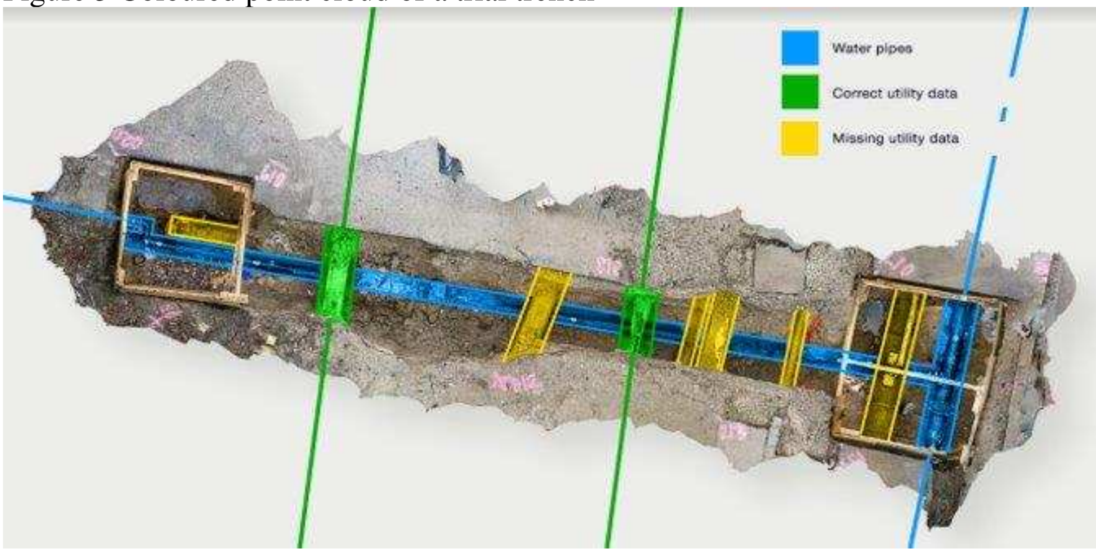

Figure 4 Documentation of a trial trench as CAD-drawing on top of point cloud

4 COMPARISON, CONTEXTUALISATION OF THE SITUATION AND LESSONS LEARNT

The two cities of Singapore and Zurich are very comparable in terms of their economic strength (gross domestic product per capita), attractiveness (population growth) and the related construction activities. In both cities, the digital transformation is well advanced and the property cadastre has been available digitally for many years. Regarding the underground cadastre, the differences are large, as described above. As part of the Digital Underground project, several reasons for the lack of a joint underground cadastre in Singapore were identified. The following list provides an overview:

- Lack of legal obligation to collect (and provide) data on underground utilities: In some cases, there are several owners per asset, particularly in the case of telecommunications. For commercial reasons, owners do not want to voluntarily share information about their infrastructure.

- Easier road construction: Opening a road for trial trenches or underground construction is much cheaper in subtropical Singapore than in the harsher climate of Zurich. In Zurich, a road is constructed in several layers. Due to weathering and deterioration, they must be completely and extensively renovated on average every 20 years. Afterwards, the road body should remain as intact as possible to protect the structure. A great deal of effort is therefore put into coordinating the road construction with the construction/updating of underground infrastructures.
- Time constraints: In Singapore, roads with construction sites must be reopened at the start of rush hour. As a result, utility construction is carried out in short sections and the time window available for measuring the new conduits or pipes is very limited. In Zurich, road closures or deviations due to construction sites usually last several weeks and the works are therefore easier to plan.
- Data access: The exchange of geodata between the authorities is very open in Zurich due to the corresponding legislation and in many cases the data is also accessible to the entire population. The security situation is perceived differently in Singapore, as is the accessibility of data.
- Responsibilities: The organisation of the state administration in Singapore allocates responsibilities centrally while the federal structure in Switzerland results in distributed responsibilities.

What might be the impact of the federal structure on the utility cadastre? In contrast to the real estate cadastre managed by surveying offices, a subsurface utility cadastre is a joint effort of a wide variety of organisations. This is complicated by the fact that in not all asset owners belong to the public sector but are at least partially organised under private law. It is therefore necessary to harmonise these different organisations with their processes, specifications and individual needs for confidentiality of data about their own utilities and sufficiently free access to data about other organization’s utilities. This must be accomplished in such a way that the data can be merged and mutually released for use in planning and construction. To simplify the exchange of data between a wide variety of systems, a neutral data exchange format and data structure is to be preferred. In Switzerland's federal structure, such cooperative approaches are common practice.

5 CONCLUSION

As mentioned in Chapter 3.2, the "Digital Underground" project has shown that many asset owners in Singapore (as in other cities) have a documentation of their supply network and keep it up to date. However, with a view to intensifying the use of the underground, it is also clear that the situation in metropolitan areas like Singapore needs to be improved, i.e., there needs to be centralised access to a system with all utility data and the data needs to be harmonised and of sufficient quality. However, the development of a nationwide, cross-domain product of uniform data quality is a major challenge. In the project different elements to improve the situation and to build a system called "Singapore Digital Underground" were identified. These elements are probably also decisive success factors in many other cities. Of highest relevance are not the technical aspects, but much more the organisational aspects as given in the following list:

Governance

- A digital twin of the underground must be considered as a supra-organisational product which requires a clearly defined and strictly followed (data) governance.
- Since the product is a combination of many datasets, someone must ensure the overall quality. Preferably, this should be the provider of the spatial data infrastructure (SDI). The detailed regulations necessary for this are to be worked out.

Policy and legal

- The existing legal bases need to be modified or supplemented to enable the envisioned product development. Investigations should focus on the ability for the SDI provider to enact its role as developer of the digital twins, on the roles and responsibilities of asset owners but also the professionals (surveyors) for the correct mapping of the features.
- In terms of legal regulation, governance, and organisation, it should also be noted that some asset owners are not only active in one city, but across several administrative units. The service areas are therefore not always uniform. Legislation must take these circumstances into account, and it is important to clarify how the data management effort for asset owners can be minimised.

Financial matters

- It must be determined who carries the responsibility and financial burden for utility survey and data management.
- It must be agreed between all actors who carries the responsibility and financial burden for product management including the continuous improvement of the technical infrastructure.

Processes and standards

- Procedures must be developed and agreed so that the surveying of newly installed pipe sections can be carried out in open trenches.
- Further standards must be developed for the surveying of underground infrastructure and the completion of data collection in the GIS. Ideally, all other underground elements should also be surveyed in this context if they are not yet recorded in the underground cadastre.
- A process for the data flow needs to be defined.
- Technical standards for the automatic exchange and transfer of data between systems must be established to ensure efficient operational organisation and a high degree of data timeliness.

Platform and data

- A platform for the data aggregation and the publication of the digital twin of the subsurface infrastructures must be developed and deployed. Special attention may need to be paid to security measures and access restrictions.
- Over time, continuous quality evaluation measures must be implemented to support the quality management of the digital twin.

Community, capacity and education

- Existing platforms and media should be used to establish and maintain collaboration with experts from various fields. They should also be used to communicate proactively about the project and developments and to seek feedback.
- Figures and indicators should be identified for assessing whether the current capacities and competences meet the new requirements and whether any potential deficits can be addressed quickly.
- The quality of the resulting product can only be as good as the knowledge of the staff involved in data collection and maintenance. If not yet established, training must be organised.

As mentioned, the technical aspects are less important than the organisational ones. The effort required to develop and regulate these various issues should not be neglected. It generally requires an investment of time and resources.

At the technical level, the main question is whether and how the existing data can be validated and improved to meet today's requirements. As much of the infrastructure for operation and maintenance on the road surface is visible and easy to survey, such as manhole covers or cabinets, these could be used to improve georeferencing and to check the plausibility of completeness. This would allow the initial creation of the digital twin to take place in a shorter time and offer better data quality. Further investigations must follow in order to concretise these options.

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BIOGRAPHICAL NOTES

Dr. Juerg Luethy is Director of Geomatik + Vermessung at the City of Zurich, the office for cadastral surveying and spatial data infrastructure at Switzerland's largest city and most important business location. He obtained a master's degree in 1996 from Federal Institute of Technology Zurich (Switzerland) in Rural Engineering and Survey. From the same institution he holds a PhD (2007). He has a wide experience in the digital transformation of spatial data and the operation of Spatial Data Infrastructures. He is the Swiss delegate to FIG Commission 7. Since 2016 he is president of SLM Swiss Land Management Foundation.

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Victor Khoo is a Director of the Survey at the Geomatics Division at the of Singapore Land Authority (SLA). He received his Ph.D. and Master of Engineering from the Nanyang Technological University (NTU), Singapore and his Bachelor degree in Land Surveying from the University Technology of Malaysia (UTM). Victor is a Registered Surveyor; a professional surveyor registered under the purview of Singapore’s Land Surveyors Act. He works in diverse geospatial related subjects that encompass the collection, management, and dissemination of geospatial data. His specific areas of interest include Differential GPS, Cadastral Surveying and Spatial Data Infrastructure.

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