Reducing Damage to Underground Utility Infrastructure during Excavation

Costs, benefits, technical advances, case studies, and recommendations

Prepared for the Geospatial Information & Technology Association

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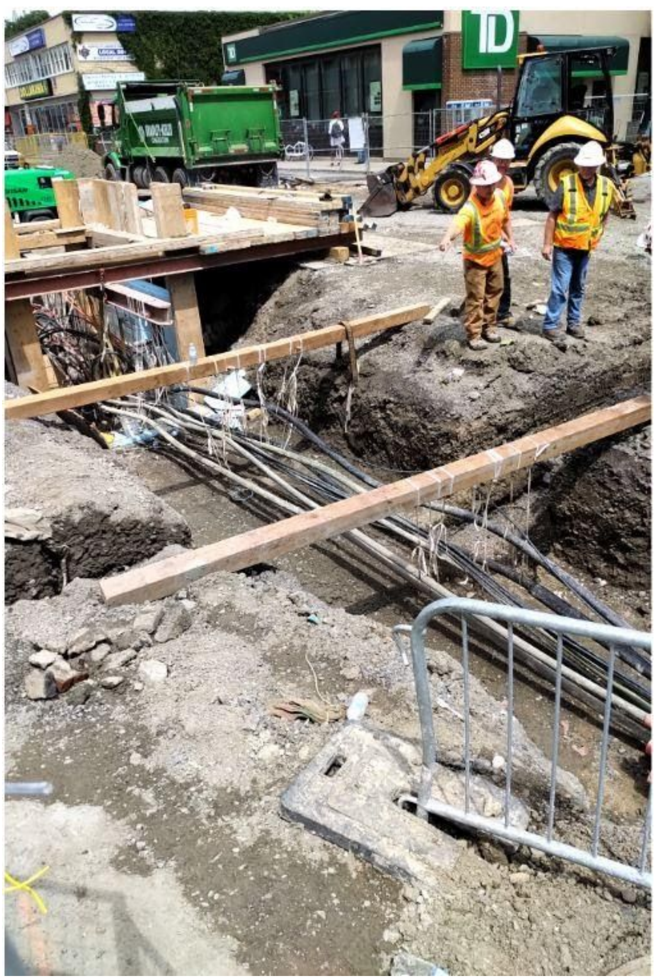

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Introduction

Every year there are injuries and fatalities attributable to hitting underground infrastructure during excavations. In addition inaccurate and missing information about underground infrastructure is a major cause of construction project schedule and budget overruns. It has been estimated that unreliable location information about underground infrastructure represents a $50 billion to $100 billion drag on the U.S. economy, multiple £ billions in the U.K. and € 1 billion in the Netherlands. In the United States it is estimated that $10 billion is devoted annually to locating underground infrastructure during construction, but the available statistics indicate that this is not reducing the number or severity of incidents of underground utility damage.

It is revealing to compare underground utility damage in the United States and Japan. The comparison reveals a startling difference in the annual number of incidents of underground utility damage during construction. In the U.S. there are between 400,000 and 800,000 incidents per year (roughly one or two every minute). For Japan the number of incidents in 2016 was 134. Clearly something can be done to reduce the risk for construction workers and the public.

Without accurate maps of underground infrastructure, every construction project has the potential to become a disaster site. Nearly every month the news carries reports of explosions caused by damage to underground utilities during construction excavation. In the last year there have been explosions in Murrieta, California (July) where a utility worker was killed and 15 others injured, downtown San Francisco (February), Durham, North Carolina (May)... In February 2019 Columbia Gas of Massachusetts agreed to pay a $53 million fine for a series of gas explosions in Merrimack that killed one person and destroyed dozens of homes. The NTSB board investigating this incident stated that it found it amazing that the asset owner could not produce a plan of the underground infrastructure on a timely basis. These incidents are more frequent than many people realize. Unlike the aviation industry where reliable data is collected and is accessible to investigators to reduce the risk of disasters happening in the future, there is limited access to data about the location of underground infrastructure. Furthermore, what data is accessible is inaccurate, out-of-date and incomplete. The result is that unlike the civil air transportation industry where there has been a continuous reduction in serious accidents, during construction incidents, some with injuries and fatalities, continue to occur with no signs of reduction in frequency or severity.

In addition, inaccurate and missing information about underground infrastructure increases the risk of construction project schedule and budget overruns. According to the Federal Highway Administration (FHWA) missing or inaccurate location information about underground utilities is a major source of highway construction project delays. It has been estimated that the inability to locate underground infrastructure represents a $50 billion drag on the U.S. economy and up to a £6 billion ($7.5 billion) drag on the U.K. economy. The major problem facing the construction industry in advanced economies is productivity which has plateaued or even declined over the past 40 years. With the growth of private investment in infrastructure, improved productivity has become urgent. McKinsey has made the case that BIM and geospatial are key technologies in transforming construction. The U.K. has been a leader in the digitalization of the construction industry, mandating that from 2016 all public construction in the U.K. must use a BIM Level 2 process. The subsurface has been for the most part ignored in the application of digital technology to construction, but there are signs now that this is changing as people recognize the drag on construction projects and the broader national economy that this represents. Improving the reliability and sharing of location information about the underground can be seen as 'low hanging fruit' in the quest to improve construction productivity.

Lastly, an increasing number of cities and authorities around the world are realizing that a lack of reliable information about underground infrastructure may lead to planning decisions that result in a less than optimal allocation and use of the underground space under their purview. In dense urban areas in particular, underground space is a scarce resource that is often already congested. Future developments such as energy transition, 5G communication, rehabilitation and replacement of existing infrastructure, and ambitions to bring many elements of the city itself underground to cope with a lack of available space above the surface necessitate the need to treat the underground space as an asset which needs to be managed with care and its value optimized throughout its extensive lifetime. Improving the reliability of information about underground infrastructure can be expected to lead to more efficient and safer allocation of underground space, ultimately leading to increased infrastructure resilience and reduction of opportunity cost.

This is not an impossible challenge. A number of cities, regions and countries around the world have recognized the importance of accurate information about the location of underground infrastructure and implemented processes to reduce the risk of these events. In this white paper a number of these international initiatives will be reviewed to identify the key elements required for a successful program to reduce underground utility damage during construction.

Cost of underground utility damage

Several jurisdictions have attempted to estimate the cost of underground utility damage for individual incidents and for entire national economies. Costs can be broken down into direct costs and indirect costs. Direct costs include the costs of sending a crew to repair the damaged pipe or cable. Indirect costs include many factors that are often hard to quantify such as traffic disruption, injuries and fatalities among workers and the public, and the lost custom that local businesses experience.

UK

About 4 million excavations are carried out on the UK road network each year to install or repair buried utility pipes and cables.

Research at the University of Birmingham on 3348 incidents of damage to underground utilities determined the direct costs of utility damage during construction.

Facility	Avg cost per strike in 2016
Electricity	£ 970
Gas	£485
Telecom	£400
Fibre-optic	£2800
Water	£300-980

The researchers found that the true costs associated with utility strikes is much higher than this. Direct costs include the costs of sending a crew to assess and repair the damaged pipe or cable. Indirect costs include the impact of traffic disruption as a result of the strike, any injuries and other impacts on the health of the workers directly involved and the public in the immediate neighbourhood, and the lost custom that businesses experienced as a result of the traffic disruption. The research revealed that the true cost is about 29 times the direct cost. This is a startling result which indicates that the cost to society of underground utility strikes is much, much larger than is generally believed.

US

The CGA compiles information on the direct cost of damage to underground infrastructure for different types of underground infrastructure.

Facility	Avg cost per damage 2016
Natural gas	$5,914.00
Telecom	$3,022.00
Electric	$4,905.00
Cable TV	$2,190.00
Water	$3,003.00
Sewer	$5,163.00
Liquid pipeline	$7,711.00
Steam	$1,800.00
Average	**$4,021.00**

At an average cost of $4000 per hit, the CGA estimates that the direct cost to the U.S. Economy is about $1.5 billion (or roughly double this if the number of incidents annually is actually closer to 800,000). The CGA emphasizes that this is a conservative minimum estimate and does not include indirect and social costs. Scott Landes, of Infrastructure Resources LLC, has compiled a comprehensive list of the direct, indirect and societal cost of damage to underground infrastructure.

Items that may or may not be collected

- External collection costs/agency commissions
- Barricades/traffic control

- Permits (city/county/state/provincial) to install replacement cables/pipelines
- Legal fees and litigation costs
- Exposing the damage for repair
- Materials used in repair
- Restoration of the area
- Actual cost of internal labour
- Heavy equipment used
- Generator/power equipment
- Food, lodging, and travel expense
- Emergency mobilization (contractor/locator)

Time

- Damage investigation, on-site and follow-up
- Internal staff collection efforts
- Out of service complaints
- Insurance resolution discussions
- Overtime for unexpected increases in workload
- Employee time/travel for depositions/trial

Overlooked/difficult to track

- Lost customers
- Customer loss of use (refunds/credits)
- Resolution of customer complaints
- Engineering/reengineering due to damage
- Establishing outage bridge to coordinate services interruption
- Support staff (3-20) for outage bridge
- Workload delays
- Future failure points (damage may weaken system and lead to future failure unattributed to 3rd party)
- Damage data capture and submission (software and/or manual)

- Emergency on call ticket notifications
- Facility owner records updates
- Reporting requirements (FAA, 911, PHMSA)

Soft costs

- Loss of brand confidence
- Negative public feedback
- Difficulty maintaining customer relationships, especially large businesses, with inconsistent services

Societal costs

- Loss of 911/emergency services
- Business closing
- Employee downtime
- Road closures/traffic delays

This is a very interesting list because it provides a perspective on the comprehensive impact on society of disruptions to utilities and telecom resulting from underground damage during construction.

If the ratio of total to direct cost determined by the researchers at the University of Birmingham is applicable to the US, it would mean that the total estimated impact of unknown or poorly located underground infrastructure on the U.S. economy is between $50 billion and $100 billion annually.

Netherlands

Network operators are required to report all incidents of damage to their infrastructure including location, cause and other information. Based on this and other information Kadaster publishes an annual report with statistics on underground utility damage. This information can be used to estimate direct costs of damage to underground infrastructure.

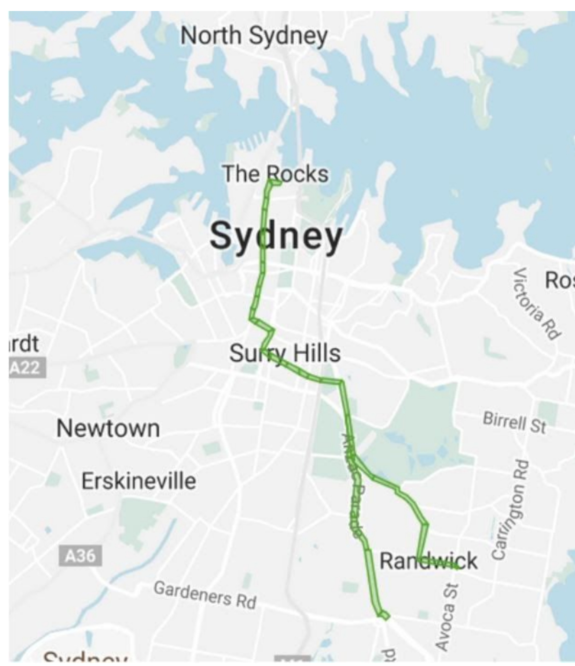
Damage to underground utilities in 2018	
Annual excavation damage	41,169
Direct costs from damage	€ 34,500,000
Average repair cost per excavation damage	€ 838

If the estimated direct cost is multiplied by 29X from UK research to estimate the total cost, underground utility damage costs the Dutch economy about € 1 billion annually.

An important conclusion from the research into the cost of underground utility damage is that it represents a major drag on national economies, $50 to $100 billion annually in the U.S., £ billions in the U.K., and € 1 billion in the Netherlands.

Examples of the benefits of accurate maps of underground infrastructure for construction projects

Sydney Light Rail



The Sydney Light Rail Project is a $2.1 billion PPP project for 12 km of light rail to be completed by 2019. Prior to awarding the contract for construction the Department of Transport for New South Wales undertook 12 months of night work to map 5,000 subsurface utilities along the route. 500 existing subsurface utilities were identified for relocation to make way for the new light rail infrastructure.

The first problem that was encountered was that as-built information from utility providers was frequently unreliable - incorrect location, incorrect materials, and so on - which caused disruption and delays with construction. The second problem was that during construction an additional 400 unknown services, not on the DoT maps, were found. Each of the unknown utility services that was encountered had to be treated as potentially live and all utilities in the area had to be contacted to try to identify the service, a process that typically required a month for each utility. Of the 400 unknown services that were found, a few were claimed by one of the utilities, but most of the unmapped services were found to be no longer in service. Unnecessary costs to the construction program were incurred as a result of these unforeseen delays. In addition completing the relocation of utilities was delayed by 5 months.

ACIL Allen (3D QLD Road Map - preliminary findings. Brisbane: #D QLD Task Force 2017 reported in Economic Value of Spatial Information in NSW 2017) has estimated that if a complete and reliable 3D map of underground infrastructure had been available at the project planning stage, the project could have been completed at least one and a half years sooner, at less cost with a much lower level of risk. While the project at that time of the study remained 'on time and on budget', ACIL Allen says that this is only because the risk of delays and additional costs resulting from unidentified underground utilities were included in the contract pricing and schedule.

Construction folks will not be surprised by this. It once again points out the advantage of 3D models replacing unreliable as-builts because it enables a process that speeds up project development because it leverages existing engineering data rather than requiring a "complete resurvey" (usually incomplete with respect to underground utilities) at the beginning of every project.

Alabama DOT I-20/I-59 Corridor

For the largest construction project in the state of Alabama's history, the Alabama Department of Transportation (ALDOT) used ground penetrating radar (GPR) and other technology to create an accurate 3D model of underground infrastructure prior to designing a replacement for one of the busiest interchanges in the state. ALDOT estimates that the 3D model, which was provided to all contractors bidding on the project, saved millions of dollars and reduced the risk of budget and schedule overruns.

The location of existing underground utility infrastructure is more often than not poorly known which creates significant risk for infrastructure and highway construction projects. Typically on highway construction projects, the right of way is chosen, the highway designed and the project readied for construction before the one-call centre is contacted and the affected utilities arrive to detect and locate their underground facilities, usually in 2D. The utilities that have been detected are then moved to make way for building the highway. Not infrequently the location of the identified utilities turns out to be unreliable and during construction other unidentified utilities are encountered both of which can lead to delays and to budget overruns.

The I-20/I-59 Corridor is the largest construction project in the State of Alabama's history with a cost of $750 million. The project had a very tight timeframe. ALDOT's Design Bureau's Visualization Group was tasked to provide a complete 3D proposed model for building information modeling (BIM). The BIM model needed to provide the information necessary for multiple uses including: visualizations, design checks, construction analysis, clash detection, right-of-way negotiations, lawsuits, and aesthetics. The model had to be very accurate because it was intended to be provided to the construction bidders to enable more accurate cost estimates and lower bids.

One of the important challenges faced by this project was utility coordination because the interchange is situated in Birmingham's business district. Realizing that underground utilities can make or break a project's schedule, ALDOT invested a considerable effort in locating utilities and creating a 3D model of above and below-ground utilities. Potholing and scanning with ground penetrating radar augmented existing as-built records to enable ALDOT to create an accurate 3D model of underground utilities. 3D is important because what may appear to be clashes in 2D may not actually be. Also it was much easier to explain to utilities in 3D that a costly move of a utility line is not necessary. ALDOT's Visualization Group was tasked with detecting clashes between the proposed design with the existing conditions. Every contractor bidding on the project got the full 3D model. Because of the reduced risk associated with underground infrastructure ALDOT estimated that it saved over $10 million by using 3D modeling of underground and aboveground utilities. To date the project is on budget and on schedule. After completion of the project

ALDOT plans to retain the 3D model which can be reused for other projects in the same area.

ALDOT found other advantages of 3D modeling as well. Public and stakeholder perspectives of the project were a major concern and using the 3D model allowed the Visualization Group to provide accurate photomatches, renderings, and animation to relay project impacts to all stakeholders. While the project is under construction the 3D model is also being used by inspectors in the field so that construction details are relayed accurately to the workers.

This project provides further evidence of the significant benefits of a 3D model of underground infrastructure which can be used during design and construction to reduce the risk of utility hits, reduce the cost of utility relocations, and avoid unnecessary utility relocates.

Expo Milano

A ground breaking project to map underground infrastructure was undertaken in the Region of Lombardy in Northern Italy. This project was kicked off by a pilot project to map all underground infrastructure on the site of Expo Milano in preparation for the 2015 event in Milan.

For the Milan pilot project all underground infrastructure in the project area (230 000 square meters) including electric power, water, sewers, gas, district heating, street lighting, and telecommunication were mapped both from historical records and using IDS's ground penetrating radar (GPR) technology. A data model for underground infrastructure was developed for the different types of underground networks based on the Italian DigitPA and the INSPIRE US utility standards.

The key part of the project was the comparison of the historical records with the results captured by GPR. The analysis revealed significant discrepancies in the historic record including thousands of meters of unknown infrastructure. For the known infrastructure the average error in geolocation was about 30%, but much larger errors of up to 100% were also recorded. The conclusion is that even in Europe the record of underground infrastructure can be highly unreliable. Locating and identifying underground infrastructure can provide benefits to both network operators and local governments. For network operators it can reduce the risk of service disruptions during construction. For local governments that GPR can identify previously unknown underground infrastructure provides a financial benefit because utilities are taxed by municipalities based on the total infrastructure the utilities maintain within city limits.

The other ground breaking part of the pilot project was an economic analysis of the costs and benefits of applying GPR to detect the location of underground infrastructure. The analysis estimated that the return on investment is about €16 for every euro invested in improving the reliability information of underground infrastructure. The analysis emphasized that there were other important, but non-quantifiable, benefits including better safety for both workers and the public as well as fewer traffic disruptions.

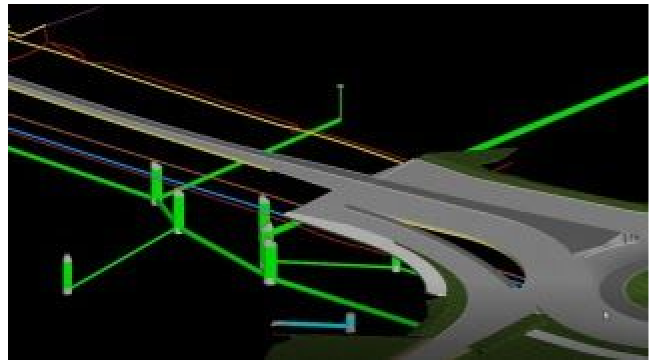
Highway revitalization project, Cedar Falls, Iowa

For a $38.9 million highway revitalization project in Cedar Falls, Iowa it was estimated that an innovative design including roundabouts would save the community $32 million over 25 years by reducing the number of accidents, decreasing travel time, lowering fuel usage and emissions, increasing property values, and leading to greater economic growth. Most importantly a 3D model of all underground infrastructure in the right-of-way was created prior to engineering design. This was an important factor enabling the project to complete on-time and 3% under budget.

University Avenue in Cedar Falls was an Iowa Department of Transportation (DOT) six-lane, divided highway which the City of Cedar Falls took ownership of in 2014. Built over 60 years ago, the corridor carries 20,000 vehicles per day and was suffering from deteriorated pavement, a crash rate 20% above the state average, a lack of pedestrian and bicycle accommodations, a pedestrian death, and inefficient traffic operations.

Innovative, advanced traffic designs were developed; multi-lane roundabouts, a dogbone interchange, and complete streets – which allowed for a reduction of lanes that still decreased congestion and increased overall traffic flow. Technical innovations included use of drone and mobile scanning utilized for reality modelling, a building information (BIM) for creating 3D models and fostering collaboration, and 3D visualization and traffic modelling for communicating alternative designs to stakeholders and the public.

One of the most innovative aspects of the projects was the development of a 3D model of underground utilities before the start of the design phase. This enabled the detection of 200 utility conflicts during the design phase avoiding utility conflicts during construction and was the primary reason that the project completed on schedule and 3% under bid saving the City $700,000.



From a public safety perspective, Foth estimated an 89% reduction in personal injury accidents. As owner of the highway, the City is projected to realize $27 million in benefits from economic growth, corridor improvements, avoided traffic signal maintenance, and reduced lighting costs. Reality modeling including mapping underground utilities prior to design, innovative highway design, and digital design technology based on BIM saved $521 thousand in project costs by eliminating utility conflicts and the resulting change orders, enhanced public engagement, and design acceleration.

Despite facing aggressive schedules, the challenge of information coordination, complex utility coordination, intense public involvement, and a very tight design schedule involving public participation, Foth was able to deliver the project on time and below budget.

Natural gas pipeline, Washington State

In a major Puget Sound Energy gas line construction project, an eight inch high pressure natural gas pipeline along a major highway SR510 managed by the Washington Department of Transportation, the design engineers Utility Mapping Services (UMS) diverged from normal construction practice by first creating a 3D model of the existing underground and above ground infrastructure. During construction there were no utility strikes and as a result there were no change orders and the construction project was completed in 7 instead of the expected 10 weeks.

A major risk for the project was that the corridor includes complex utility infrastructure woven through dense commercial and residential areas with limited right-of-way and heavy traffic congestion. Because of the complexity of the underground utility infrastructure it was decided at the beginning of the project to develop a 3D model of the existing underground infrastructure. The model enabled the design team to adjust the pipe elevation and horizontal alignment to avoid potential utility conflicts during the design phase. The 3d model of existing utility infrastructure avoided unnecessary utility relocations and the associated construction delays and contractor change orders. It also allowed for tighter contractor bid estimates by providing a more accurate design to the contractors.

UMS' subsurface utility engineering (SUE) services group were familiar with new remote sensing technology such as ground penetrating radar (GPR) and electromagnetic detection which allowed them to acquire 3-D location data for underground utility infrastructure. Application of new SUE technology created much greater value for the customer because UMS could now clearly convey to the client the issues presented by existing infrastructure and work with their design and construction teams and the utility infrastructure owners to minimize utility relocations and avoid surprises from buried unknowns.

Starting with a 2D basemap, the underground survey was conducted using several technologies, including electromagnetic and GPR, and potholing for validation. In addition to the expected utility infrastructure, the survey detected undocumented abandoned utility lines which highlights an important advantage of the new remote sensing technologies. The data was captured and integrated to create a 3D model.

The 3D model formed the basis for the design for the new gas pipeline and enabled designers to avoid expensive and unnecessary relocation of utilities. The 3D model detected 170 conflicts, points of intersection of the design for the new pipeline with other utilities. Several alternative routes were assessed and the costs and benefits of each were computed and compared in order to determine the optimal routing for the new pipeline. 3D visualization of the alternative routes helped the designers show Puget Sound Energy and the Washington DOT the advantages of alternative routes and allowed changes to be made to the design live in front of the customer.

Another important aspect of this experience is that the design had to avoid conflicting with a new sewer line which had not been built yet - one of the existing sewer lines was scheduled to be replaced by a significantly larger one in the near future. This highlights the importance of not only knowing the location of existing underground infrastructure but also planned future work. Sharing planned work enables improved works coordination and avoids repeated excavations in the same stretch of road. This is especially important in jurisdictions that limit planned excavations to once every five years for example.

When automated excavation was used, the 3D model made it possible to create exclusion zones that prevent the machinery from striking underground utility infrastructure.

The 3D model helped in other ways. The project required two variances from the Washington DOT which were granted in record time because the 3D model showed so clearly why and where they were required. The 3D model helped to minimize highway disruptions to the public. Most critically from a safety as well as cost perspective, there were no utility strikes on the project. As a result the 3D model is credited with reducing construction time from 10 to 7 weeks. Most importantly from a budget perspective, there were no change orders and the total cost of the project came in at 10-15% less than estimated in the absence of a 3D model.

ROI analyses of conducting a subsurface utility engineering (SUE) survey as part of construction projects

Several return on investment (ROI) studies of subsurface engineering utility engineering (SUE) surveys applied to highway construction projects have been conducted since the late 1990s.

One of the first in 1999 by Purdue University and sponsored by the USDOT Federal Highway Administration (FHWA) identified 21 categories of cost savings that could result from including a subsurface utility engineering (SUE) survey in construction projects. Only some of these could be quantified and it was estimated that the qualitative benefits exceeded those that could be quantified. It was estimated that SUE surveys resulted in construction savings of at least 1.9 percent over the traditional approach of relying on as-builts and (above-ground) site surveys for identifying underground utilities. Using the national expenditure in 1998 of $51 billion for highway construction (FHWA), it was calculated that requiring SUE on road construction projects could result in a national saving of at least $1 billion per year.

Year	ROI	Cost of SUE (% of project cost)	Description	Sponsoring agency	Source
2012	11.39 : 1	1.65%	Study of 22 SUE and 8 non-SUE projects	PennDOT	Yeun J. Jung, Evaluation of subsurface utility engineering for highway projects: Benefit–cost analysis, pages 111-122 in Tunnelling and Underground Space Technology Volume 27, Issue 1 Pages 1-168 (January 2012)
2012	16 : 1		Study of one SUE project	Region of Lombardy	
2007	22.21 : 1	0.6 %	Study of 10 SUE projects	PennDOT/US DOT FHWA	SUBSURFACE UTILITY ENGINEERING MANUAL PennDOT/MAUTC Partnership, Work Order No. 8 Research Agreement No. 510401 FINAL REPORT August 20, 2007 By S. K. Sinha, H. R. Thomas, M. C. Wang and Y. J. Jung
2004	3.41 : 1		Study of nine SUE projects	Ontario Sewer and Watermain Contractors Association	Osman, Hesham, El-Diraby, Tamer E., 2005. Subsurface Utility Engineering in Ontario: Challenges & Opportunities. A Report to the Ontario Sewer & Watermain Contractors Association, October 2005.
2004	12.23 : 1	1.39%	Reanalysis of 71 SUE projects	ASCE based on USDOT data	Jeong, H.S., Abraham, D.M., Lew, J.J., 2004. Evaluation of an emerging market in subsurface utility engineering. ASCE, Journal of Construction Engineering and Management 130 (2).
1999	4.62 : 1	0.5 %	Study of 71 SUE projects	USDOT FHWA	Lew, J.J., 2000. Cost Savings on Highway Projects utilizing Subsurface Utility Engineering. Federal Highway Administration, Washington, DC.

A subsequent reanalysis of the same Purdue data estimated that the ROI was $12.23 for every $1 spent on SUE. Furthermore the cost of conducting a SUE survey was estimated at 1.39% of total project costs. In 2007 a study for PennDOT and USDOT found an ROI of 22.21 : 1.

The most recent ROI analysis sponsored by PennDOT differed from previous analyses by including both SUE and non-SUE projects. It calculated an ROI of 11.39 : 1. The largest contributor to the cost savings attributed to SUE was a 40.33% reduction in utility relocation costs. Utility relocations were avoided or reduced by providing engineers/designers with accurate underground information in the early stages of design. The second largest savings was 29.46% in reduced construction and design costs. SUE enables designers to design efficiently and accurately with reliable information, so that design time can be saved and unnecessary construction work can be avoided or reduced. The cost of conducting a SUE survey was estimated to be 1.65% of project cost.

These ROI studies show that SUE can provide accurate utility information with important project benefits at reasonable cost.

2012 Pennsylvania Department of Transportation

A definitive study of twenty-two projects utilizing subsurface utility engineering (SUE) and eight non-SUE projects from Pennsylvania Department of Transportation (PennDOT) districts has revealed that $11.39 can be saved for every $1 spent on SUE. The cost of conducting a SUE survey was estimated at 1.65% of total project cost. Eleven direct and indirect costs where SUE would lead to savings were considered in the analysis; utility relocation cost, utility damage cost, emergency restoration cost, traffic delay cost , business impact cost, user service cost, environmental impact cost, information gathering and verification cost, legal and litigation cost, efficient utility design and construction, and other utility related costs and benefits.

On the expense side two kinds of costs are involved in conducting a SUE survey. One is the use of geophysical techniques such as EMI and GPR to identify the location of underground utilities and other objects. The other is potholing (using safe excavation techniques) to confirm the location of the utilities and objects identified. In this study for the projects utilizing SUE, costs were obtained directly from project accounting. For the projects that did not use SUE, costs are estimated from interviews, historical data, and individual project studies.

For the twenty-two projects where a SUE survey was conducted, all underground utilities and other objects were located to ASCE 38-02 quality level A (potholing) or B (EMI and GPR). For the eight projects utilized traditional methods, the location of underground networks was estimated to ASCE quality levels C (site visit) and D (as-builts).

Previous ROI studies of SUE only used projects where SUE surveys were performed to quantify the cost savings of SUE. In this study, non-SUE projects were used to determine the cost savings of SUE because direct costs incurred by problems that would have been avoided by SUE can be considered as SUE benefits. The results of the study revealed that $11.39 can be saved for every $1 spent on SUE on road projects. The top cost savings that were found are as follows:

1. 40.33% reduction in project relocation cost by providing accurate underground information in the early stages of design
2. 29.46% reduction in construction and design costs - SUE enables designers to design efficiently and accurately with reliable information, so that design time can be saved and unnecessary construction work can be avoided or reduced.
3. 9.59% reduction in redesign costs
4. 9.08% reduction in delay costs due to relocation
5. 6.81% reduction in delay cost caused by emergency
6. 1.41% reduction in delay cost caused by unexpected utility
7. 1.41% reduction in information gathering and verification cost
8. 1.04% reduction in restoration cost

The study also showed that the greater the complexity level of buried utilities, the higher the SUE benefits.

The cost of conducting a SUE survey averaged 1.65% of total project cost. It was concluded that SUE can provide accurate utility information with important project benefits at reasonable cost.

2012 Region of Lombardy, Italy

A pilot project was undertaken to map all underground infrastructure on the site of Expo Milano in preparation for the 2015 event in Milan. All underground infrastructure in the project area (230

000 square meters) including electric power, water, sewers, gas, district heating, street lighting, and telecommunication were mapped by combining historical records and IDS GeoRadar ground penetrating radar (GPR) technology. A key objective of the project was an economic analysis of the costs and benefits of applying GPR to detect the location of underground infrastructure. The analysis estimated that the return on investment is about €16 for every euro invested in improving the reliability of information about underground infrastructure. The analysis emphasized that there were other important, but non-quantifiable, benefits including better safety for both workers and the public as well as fewer traffic disruptions.

2007 Pennsylvania Department of Transportation

This study conducted by Penn State and sponsored by the Pennsylvania Department of Transportation PennDOT) and the U.S. DoT, Federal Highway Administration (FHWA) performed a benefit-cost analysis of 10 SUE highway projects from different PennDOT districts. The case studies were investigated by conducting interviews with utility engineers, SUE consultants, and project engineers. Site visits, analyses of project data, and detailed individual studies of the 10 SUE highway projects were also performed for this research. These projects were selected randomly from a list of projects that utilized SUE quality level A and/or B. The projects investigated in this study involved road construction and bridge replacement in urban, suburban, and rural areas. PennDOT project managers and engineers, utility owners, SUE consultants, designers, and contractors were interviewed. A savings of $22.21 for every $1.00 spent on SUE was estimated based on the analysis of the 10 projects. These projects had a total project cost (including both design and construction cost) in excess of $120 million. The costs of conducting SUE (to ASCE QL A or B) on these 10 projects were less than 0.6 percent of the total project costs. The benefit was cost savings of 15% over the traditional approach relying on ASCE QL C and D utility data.

Project costs ranged from $2 million to $63 million. The quality of the utility records for these projects was poor or fair. The cost of conducting SUE ranged from $20,000 to $141,000 for these projects. The ratio of SUE cost to the total project cost ranged from 0.22% to 2.8%, with an average of 1.15%. SUE resulted in cost savings ranging from $65,000 to $4.5 million. The benefit-cost ratio ranged from 3.25 to 33.93, with an average of 22.21. In other words $22.21

can be saved for every $1 spent on SUE. The costs of conducting SUE on these 10 projects were less than 0.6 percent of the total project cost. Furthermore the analysis revealed a strong relationship between the benefits of SUE and utility complexity (the density of underground infrastructure). The benefit derived from performing a SUE survey increases as the underground utility complexity increases.

2004 Ontario Sewer and Watermain Contractors Association

The Ontario Sewer and Watermain Contractors Association commissioned the University of Toronto to investigate the practice of using SUE on large infrastructure projects in Ontario. Osman and El-Diraby (2005) analyzed nine SUE projects in Ontario, conducting interviews and project case studies. They identified 11 cost saving items from the 21 cost savings items used by 1999 U.S. DOT Purdue Study. The results of Ontario Study showed that the average return-on-investment (ROI) for SUE Osman and El-Diraby (2005) analyzed nine SUE projects in Ontario, conducting interviews and project case studies. They identified 11 cost saving items from the 21 cost savings items used by Purdue Study. The results of Ontario Study showed that the average return-on-investment (ROI) for SUE ranged from $1.98 to $6.59 with an average of $3.41 for each $1 spent.

1999 U.S. DOT Federal Highway Administration

In a study conducted by Purdue University Department of Building Construction Management for the U.S. DOT Federal Highway Administration, a total of seventy-one projects (71) from Virginia, North Carolina, Texas, and Ohio were studied. The total construction costs of these road projects were in excess of one billion dollars and involved interstate, arterial, and collector Roads in urban, suburban, and rural settings. DOT project managers, utility owners, constructors, and designers were interviewed.

Based on Interviews and surveys of DOTs, utility owners, SUE consultants, and contractors 21 categories of cost savings were defined to quantify the savings in terms of time, cost, and risk management. The 21 categories of cost savings identified in the study were as follows: reduction in unforeseen utility conflicts and relocations; reduction in project delays due to utility relocates; reduction in claims and change orders; reduction in delays due to utility cuts; reduction in project contingency fees; lower project bids; reduction in costs caused by conflict redesign; reduction in the cost of project design; reduction in travel delays during construction to the motoring public; improvement in contractor productivity and quality; reduction in utility companies' cost to repair damaged facilities; minimization of utility customers' loss of service; minimization of damage to existing pavements; minimization of traffic disruption, increasing DOT public credibility; improvement in working relationships between DOT and utilities; increased efficiency of surveying activities by elimination of duplicate surveys; facilitation of electronic mapping accuracy; minimization of the chance of environmental damage; inducement of savings in risk management and insurance; introduction of the concept of a comprehensive SUE process; and reduction in right-of-way acquisition costs.

The reduction in risk for all of these potential benefits by conducting a SUE survey has been difficult to quantify. Benefits have been categorized as exact costs that can be quantified in a precise manner, for example the cost of potholing or the cost to eliminate utility conflicts; estimated costs that are difficult to quantify, but can be calculated by studying projects in detail, interviewing the personnel involved in the project, and applying historical cost data; qualitative costs that cannot be estimated due to a lack of data, for example, for example, avoided impacts on nearby homes and businesses.

The analysis revealed savings ranging from $0.34 to $206.67 for every dollar invested in SUE with an average of $4.62. The cost of conducting SUE surveys on these projects was less than 0.5 percent of the total construction costs. SUE surveys resulted in a construction savings of 1.9 percent over the traditional approach of relying on as-builts and (above-ground) site surveys for identifying underground utilities. Using this ratio and a national expenditure in 1998 of $51 billion for highway construction (FHWA), it was estimated that requiring SUE on road construction projects could result in a national savings of at least $1 billion per year.

The qualitative savings were non-measurable, but it is clear that those savings are also significant and may be many times more valuable than the quantifiable savings. The study concluded that SUE is a viable, cost effective practice that reduced the risks associated with existing subsurface utilities resulted in significant quantifiable and qualitative benefits.

2004 American Society of Civil Engineers

A subsequent reanalysis of the data from the 1999 USDOT Purdue Study found that the estimated benefit of conducting a SUE survey was a cost savings of $12.23 for every $1 spent on SUE. The largest contributors to the cost savings derived from SUE were as follows:

1. 37.1% reduced number of utility relocations
2. 19.3% reduced claims and change orders
3. 11.6% reduced accidents and injuries
4. 9.6% reduced project delays
5. 3.5% reduced right-of-way acquisition costs
6. 3.3% savings in risk management and insurance
7. 15.5% other

The analysis concluded that the average ratio of the cost of SUE to total project cost ranged from 0.02% to 10.76% with an average of 1.39%.

Advances in technology

Utility locating involves remote-sensing and safe excavation technologies for identifying, detecting, and labelling underground utility infrastructure including telecommunication, storm and sanitary sewers, water, electricity distribution, natural gas, cable television, fiber optics, heating and others. Underground locate practitioners use all the information that is available to them including as-builts (however unreliable), site surveys, remote sensing tools such as electromagnetic induction, ground penetrating radar, and other techniques, and potholing. The most reliable approach is potholing using hydraulic or vacuum excavation and hand tools, but it is time-consuming, expensive at an estimated cost of $30,000 per hole, dangerous in heavy traffic and disruptive because it typically requires lane closures.

Remote-sensing tools for detecting underground objects have been available for decades. These technologies include electromagnetic conductivity (EM), ground penetrating radar (GPR), inertial, acoustic, very low frequency (VLF) profiling, electrical resistivity imaging, borehole geophysical and video logging, crosshole seismic testing, seismic tomography, microgravity surveys, seismic refraction, and magnetometry. Industry standard tools are electromagnetic induction and detection (EMI), which can only detect metallic objects and has limited vertical accuracy and ground penetrating radar (GPR) which can detect nonmetallic objects and provide 3D location, but is not reliable with certain soil types. Interpreting GPR scans has required a trained geotechnologist, which has limited the adoption of GPR by surveyors and other potential users. Furthermore, most EMI and GPR devices are intended to operate at a walking pace making them dangerous and inefficient for large scale surveys.

Recently there has been accelerating innovation in advancing technology for detecting underground infrastructure by startups and by established firms such as Leica Geosystems and Bentley. Recent advancements to the remote sensing technologies commercially available for detecting underground infrastructure are enhancements in GPR and the development of inertial locating and acoustic surveying.

Ground penetrating radar

In the last few years there have been significant advances in ground penetrating radar for detecting underground utilities. One of the areas that has already shown practical results is faster capture of GPR scans. Another area that is already showing practical results is the development of post-processing software to aid in interpreting GPR scans to identify underground objects. An area of active research (at the University of Birmingham) is the integration of geotechnical data about the subsurface into the interpretation of GPR scans.

Capturing ground penetrating radar scans of below ground infrastructure data at roadway speeds would be an important step toward efficiently and safely creating 3D maps of the underground. Furthermore advances in software are making it easier for non-geotechnical professionals to interpret GPR scans.

Hexagon AB/Leica Geosystems acquired IDS GeoRadar, an Italian radar technology company,

several years ago. For a GPR survey in London an IDS Stream-EM array was combined with a Pegasus Two LiDAR scanner to capture above and below scans with a towed trailer at up to 15 km/hour. T2 Utility Engineers, based in Whitby, Ontario, reported commercially using a Hexagon IDS GeoRadar Stream EM multi-channel ground penetrating radar (GPR) array towed at 10-12 km/hr to capture subsurface data. In Singapore, the Stream EM GPR was deployed to capture scans below a road surface of in total around 90 km length in various parts of the city-state in a series of case studies aimed at evaluating the feasibility of the technology for the improvement of the quality of existing geospatial data on subsurface utilities.

In a separate initiative a successful proof of concept in Mississauga, Ontario was reported by DGT Associates in which a Siteco rig combining a Faro mobile laser scanner and Sensors and Software GPR arrays collected data simultaneously above and below ground at roadway speeds of 80 to 90 km/hr.

ImpulseRadar, a company based in Malå, Sweden, has developed a unique ground penetrating radar (GPR) technology which uses real-time sampling (RTS) to gather data thousands of times faster than conventional GPR. The new Raptor® GPR array is designed to be fitted to a survey vehicle, which supports an arrangement of up to 18-channels. The real-time sampling (RTS) technology implemented by ImpulseRadar enables very fast collection of GPR data at speeds in excess of 130 km/hr. @ 5 cm point intervals. This is much faster than conventional GPR systems which typically operate below 15 km/hour. This enables the Raptor® GPR array to collect 3D GPR scans at posted highway speed limits. High precision positioning of the data can be achieved with RTK GPS or robotic total stations in areas of poor

GPS coverage. Talon® acquisition software displays data from all channels and depicts the position of the array and the swath of 3D GPR coverage with a moving map in real time while surveying. In addition capturing GPR data does not require highly-trained personnel. OF course, post-processing the GPR scans to create 3D maps of the below ground infrastructure requires qualified, skilled personnel. Post processed 3D data can be converted to line data for export to CAD for the depiction of utilities in a 3D survey utility/top map.

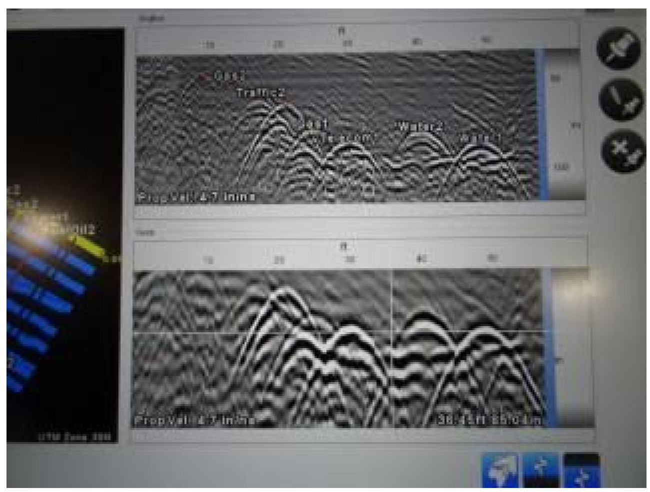
A recent project involved mapping utilities at 36 rail grade crossings in 3D. The project was for a new commuter rail expansion along an existing rail right of way. The scans resulted in 3D maps of utilities that were previously shown on existing records and identification of additional utilities that were not recorded on maps. The higher quality subsurface utility information reduced the need for unnecessary vacuum excavation test holes with an estimated cost of $1,000 per hole. Test hole results are currently running 90% in very dense corridors demonstrating the value of this approach by eliminating expensive "dry holes" and reducing risk of utility damage during excavation.

Using ImpulseRadar's GPR technology GEL Solutions LLC and David Evans and Associates Inc implemented a multi-sensor system that enables them to perform above and below-ground 3D surveys. The system combines LiDAR, photogrammetry, and the Raptor array. The LiDAR and and photo cameras and the GPR can be mounted on a vehicle to capture data at speed-limit speeds. In a pilot project in Redlands, California above and below ground scans were captured over the same corridor and post-processed to create a 3D model of the infrastructure that lies above and below the surface. Ground-painted markouts showing the positions of the underground utilities from conventional EM locate methods were extracted and georeferenced to features such as poles, pull-boxes, and other objects.

Earth Radar, based in Brisbane, Australia has been developing and commercially using new radar technology. Originally reported at the *NDE/NDT for Highways and Bridges: Structural Materials Technology (SMT)* conference, in August 2010 in New York City, Noise-Modulated Ground Penetrating Radar (NM-GPR) is a GPR variant that uses coded signal modulation and efficient receiver hardware to enable traffic-speed data capture. It was developed in Australia by Radar Portal Systems and a first generation version was used starting in 2008 for a range of road investigations for the Queensland Department of Transport and Main Roads.

One variant, called Sparas, is a trailer based 3D GPR that measures 30 points across a 2.5m width. It is normally configured to collect measurements at 60mm intervals along the road at speed of up to 100 km/hour. Referred to as noise-modulated or coded signal GPR (NM-GPR), the core technology uses a simplified approach to radar hardware that combines many fast low-fidelity measurements to create a high-fidelity image of the subsurface. The technology is able to retain the good resolution of high-frequency antennas to greater depths than conventional GPR systems can, without using different antenna sizes. Under typical soil conditions it is capable of detecting objects in high detail down to 1.5 to 2 meters and in good conditions down to 3m. Earth Radar has also developed UtiliVision software to assist in interpreting the scans and turning the data into 3D maps. In a recent commercial project in the Gold Coast, these technologies were used to cover 7.5 km of highway lanes and numerous side streets in just over 15 hours of scanning. More than 2000 subsurface utilities were later detected and mapped using these measurements.

Interpreting GPR



The major inhibitor to broader use of ground penetrating radar for detecting the location of underground utilities is the difficulty in interpreting radar scans. The technology report *Technology Advancements and Gaps in Underground Safety* published by the Common Ground Alliance in 2018 identified "*User-friendly GPR system to deploy for helping construction crews avoid utilities*" as an important gap. In 2019 Leica Geosystems released the DSX ground penetrating radar system that is the first to address this gap in a compact, portable system. The DSX system includes analytic software DXplore enabling GPR to be used productively without a trained geotechnics specialist by utility repair and maintenance, civil engineering and surveying companies.

Before the DSX, non-geotechnical professionals including surveyors found it a challenge to interpret GPR scans consisting of images with hyperbolas showing the reflections of RF waves from underground objects. GPR remained the preserve of highly trained geotechnical and other underground engineering professionals. There is interest among the surveying community to expand their professional offerings beyond the traditional above ground survey to include below ground surveys. Two years ago the one-button BLK360 opened up engineering grade laser scanning to a much broader professional audience. Similarly Leica Geosystems is focusing on simplicity with its new DSX device and DXplore software which it believes is going to open GPR scanning to a much broader professional community, including civil engineering and surveying companies.

The key feature of the DSX GPR device and DXplore software is analytics to interpret the GPR scans and visualize underground infrastructure in the form of tomographic images, rather than radar hyperbolas. For accurate locating the DSX supports seamless integration of positioning sensors (GNSS antennas) and is the first device to be integrated into machine control workflow through avoidance zones based on an underground utility map generated by the DSX.

The DSX workflow is very simple: import available as-builts in the area as DXF or other CAD format files into DXplore. If possible, walk the site to perform a visual inspection using an electromagnetic locator (EML) to search for power cables and conductive utilities and mark them on the ground. Define a grid for the area to be surveyed. Then walk the grid with the DSX device linked with Leica GPS/GNSS antennas with real-time feedback on the DSX's display. Create a georeferenced 3D map using the tomographic display (the software interprets the radar hyperbolas) of what was detected to manually identify suspected utilities on the display. The software then processes the captured GPR images to confirm the utility pipe or cable. You can then export a 2D or 3D vector file in a CAD compatible file format.

This may not be useful for experienced GPR practitioners. GPR experts are trained to work with B-scan/radargram data representation and interpretation, thus expert systems such as Leica DS2000 or IDS GeoRadar Stream are more suitable. But for surveyors and others who don't have GPR experience and recognize that underground surveying represents a significant business opportunity, this is being seen as a way to get their toes in the water of underground remote sensing.

LiDAR

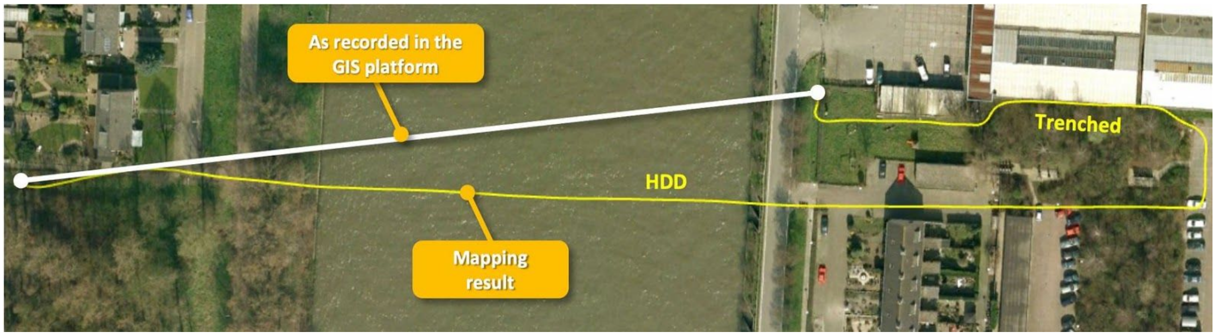
Traditionally when a new pipeline is put in the ground, its location and depth is only approximately known. Lux Modus has developed a rig and software running in the cloud that allows survey quality location information to be captured as the pipeline is constructed. The rig consists of LiDAR and photo cameras mounted on a pickup truck. The truck simply drives along the open trench after the pipe has been installed. The cameras record a point cloud and photos. The point cloud and images are uploaded for cloud processing to create an accurately georeferenced image of the pipeline that can be viewed by anyone with a browser including mobile devices.

By automatically detecting the top of the ditch and the top of the pipe, the location (x,y) and relative depth (z) of the pipe can be computed in real-time. Lux Modus uses the Unity gaming engine to enable 3D walk-throughs in virtual reality (VR) of the pipeline after the ditch has been covered. For example, this makes it possible for QA/QC people to use VR to identify weld points in the office rather than in the field.

Inertial mapping

Currently best practices for recording the location of new underground infrastructure is to survey it after installation and before covering the trench. Appropriate survey tools are total stations, RTK, and LiDAR. However, trenchless technology is increasingly being used with the result that crossbores have become a major problem in many jurisdictions. A technology that is being increasingly applied to locating pipe networks installed this way is inertial locating. Using this technology it is possible to map networks of pipes with diameters ranging from 29-34mm to 90-1500mm for distances of up to 2 km with a precision of up to 15 cm in XYZ. The output of such a system is a 3D model.

The Reduct DuctRunner inertial mapping technology is composed of an Orientation Measurement Unit (OMU) that contains inertial sensors. The OMU is battery powered and the



data logged is stored internally during a measurement run. Unlike other technologies for tracking trenchless digging does not need to be traced from above ground as it moves through a pipe. The device also contains odometers recording the speed of travel. After a run that can stretch up to 2 km, Reduct's software converts the data recorded by the OMU and odometers to an accurate 3-dimensional line that can be exported in several formats (.csv, 3D AutoCAD, or Google Earth KML file).

Acoustic locating

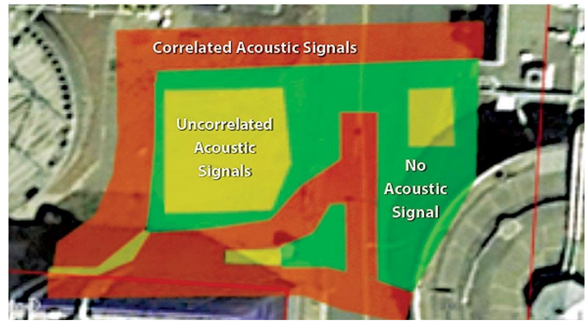
There have been significant advances in technologies for detecting underground infrastructure including inertial locating, novel radar technologies applied to ground penetrating radar (GPR), and software for post processing GPR signals to produce tomographic images. Each has its limitations. Inertial locating is restricted to known pipelines. Electromagnetic detection (EM) is restricted to conducting cables and pipes and low conductivity soil conditions. GPR can't distinguish between different types of utilities and its effectiveness is also limited under high conductivity soil conditions. Recently there is evidence that acoustic surveying may provide a technology that complements existing techniques; unlike EM and GPR methods it can detect non-metallic objects and is not affected by type of surface, soil type or moisture content.

Cartacoustics, LLC, has developed an acoustic surveying technique that uses specially crafted audible sound wave packets to locate and trace buried utilities. Sound waves are crafted into recognizable patterns and sent into the ground using special speakers. Ultra sensitive geophones then listen for reflected sound waves with the crafted patterns. Post-processing determines the time of the flight of the waves to estimate the depth of the objects that reflected the sound waves. Because of the frequencies used, the ability to detect underground objects is not affected by the type of surface (asphalt, concrete, dirt, or sod), the type of soil such as clay and the moisture content of the soils, all of which reduce the effectiveness of GPR. Acoustic locating has been successfully used in saturated soils, rocky and sandy soils, and in high-clay content soils. It has also been applied successfully with 4 inches of snow on the ground and immediately after a hard rain. In many soils GPR may be only able to detect objects a few meters down. Acoustic location is effective 30 feet or 10 meters down. The survey is non-invasive and non-destructive.

Acoustic surveying involves sampling at a number of points in the field area and then interpolating between the survey points to detect man-made structures such as cables or pipelines and their approximate locations. In addition to manufacturing the acoustic field collection hardware, Cartacoustics has also created several deliverable map products to present placement of the detected underground structures. ASTmap!™ contains a series of products that summarize the data collected in an acoustic underground survey at various levels of fidelity. A 2D map product called a DIGsafe! map highlights areas where underground structures have been located and areas that are free from acoustic returns. These areas show where it is safe to dig.. Two additional ASTmap! products provide more detailed information on depth of cover to detected structures and can be provided in various CAD formats. For a typical day-long collection, the processing and analysis takes a day or two. This means that results are generally available within a week of the survey for review.

To validate the technology Cartacoustics has surveyed a number of sites across the country. In the first such surveys they chose sites with manholes, fire hydrants, water valves and gas metering stations that are obvious indicators of subsurface structures. Acoustic surveys were conducted along the streets and right-of-ways containing these features. The acoustic returns revealed the features in the correct locations and depths as expected from nearby manholes.

Brown and Caldwell (BC) recently employed Cartacoustics' technology to survey a half-acre portion of Metro Vancouver's Annacis island Wastewater Treatment Plant (AIWWTP) in Vancouver, British Columbia. In the past, mapping underground infrastructure would have employed traditional techniques such as EMI, GPR and excavation. At this site, the soil conditions render GPR and EMI techniques ineffective, and excavation would have been required.



To acquire the needed subsurface data, an acoustic survey was conducted on a rectangular grid with 3-meter spacing between points. At each point the time of flight and horizontal location was recorded. Collected data are post-processed and detected objects were correlated from the recorded information of all surveyed points to reveal objects extending across multiple adjacent survey points and objects that were uncorrelated across adjacent points. The result of the post-processing is a 3D model of underground objects. Comparing the 3D model against the plant's engineering drawings and Building Information Model (BIM) showed a very strong correlation between expected infrastructure and the acoustic results. While the correlation was strong, the results also offered a couple of surprises – one pipe that did not follow the expected track according to the engineering drawings and several areas of uncorrelated data. This latter is suspected to represent "debris fields"; the area surveyed is in the oldest part of the plant and the "debris fields" are likely construction waste that was buried during early construction of the facility.

Many in the subsurface utilities location industry rely on a multi-sensor approach including electromagnetic detection, ground penetrating radar and other technologies. The acoustic survey results acquired to date suggest that this acoustic-based technology has the potential to add an important complementary technique to the typical underground locating quiver of EM and GPR.

Photogrammetry

Capturing underground utility location information with smartphones

Finding a way to improve our knowledge about the location of underground subsurface infrastructure is essential, but to be practical it has to be a way that does not add significantly to the cost of construction. Bentley and Costain have experimented with an efficient way of capturing enough information with an ordinary smartphone to accurately survey, map and make available via the web the location of utilities encountered during a construction project.

Performing a survey of utilities exposed during a construction project using a laser scanner and total station can be cost prohibitive and as a consequence is rarely done. A research project involving Costain and Bentley has found that photogrammetry using a consumer grade smartphone results in a 3D model of comparable accuracy to a laser scan survey and is much more cost efficient. They have also found a way to make 3D models created from the pictures captured with a smartphone available over the web.

It was shown that a simple workflow is adequate to capture enough information with a smartphone to accurately determine the location of underground utilities.

1. Mark ground control points (GCPs) around the area. They have to be visible in the pictures taken with the smartphone.
2. Take pictures from varying angles and heights around the exposed utilities with a smartphone.
3. Survey the GCPs with a total station, at least three are needed to accurately determine the location of the 3D model created from the pictures.
4. Upload the photos taken with the smartphone and process them and GCPs together to create a georeferenced 3D model of the exposed utilities.

This process has been found to result in a 3D model of comparable accuracy to a full laser scan survey and unlike a laser scan survey it is something that anybody can do. Typically it involves taking 40-60 pictures with an ordinary smartphone. After uploading the pictures, processing them

with Bentley's ContextCapture software to create the georeferenced 3D model, the resulting 3D model can be made available to others on the construction project using an online web link that allows the 3D model to be displayed along with existing 2D utility as-builts.

Capturing underground utility location information with consumer cameras mounted on excavation equipment

An alternative is to equip excavation equipment with cameras making it possible to record videos during excavation. Then a tool such as Bentley's ContextCapture can be used to create a 3D mesh showing the uncovered pipes and cables as well as neighbouring structures whose location is known. Together this information would enable the location of the underground infrastructure to be accurately determined.

Bentley has reported the results of an experiment in which four cameras, two Kodak Panorama and two Gopro cameras, were attached to excavating equipment. The resulting videos and images were then loaded into ContextCapture software to create a mesh. Analyzing the mesh allowed the location of underground pipes and cables that were exposed and the pipes that were laid to be located with centimeter accuracy by referencing neighbouring structures such as houses and other buildings whose locations were accurately known from other sources.

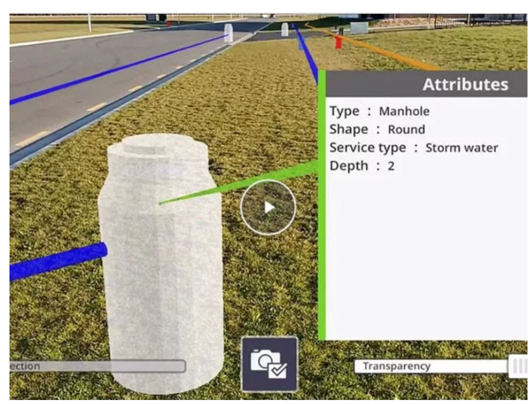
The experiment showed that if every piece of excavation equipment were equipped with low cost cameras, the location of underground utilities could be captured during excavation with no impact on the cost and scheduling of the construction project. The next step toward developing improved information about underground infrastructure would be capturing this data in a shared, open database open to all stakeholders including network operators, engineers and contractors.

Creating centimeter accurate as-builts from video captured with a smartphone

AVUS have developed a solution that allows the creation of a centimeter accurate as-built from a video taken with a smartphone. The workflow is very simple; open the AVUS app on a smartphone, enter project and site information, use the app to create a video by walking along the open trench after installation of the utility, upload the video to the AVUS cloud site, and receive the as-built in the form of .las and .dwg files. A similar process can be used with utilities exposed during construction.

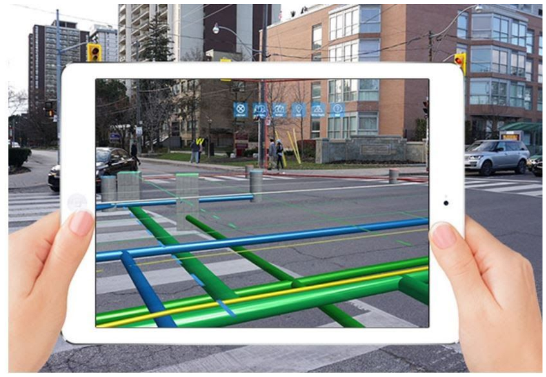
Quantum sensors

A new technology that is being applied to detecting underground utilities is measuring micro variations in gravity. Atom interferometry is being applied to create a gravity sensor which can measure a gravity gradient. This suppresses several noise sources and creates a sensor useful in everyday applications. The UK Treasury has committed £94 million to the National Quantum Technologies Program. One of the areas that is expected to benefit from quantum sensors is civil engineering, specifically in detecting objects in the underground. This is enabling university researchers, such as Nicole Metje, University of Birmingham, to research new quantum sensing technologies for detecting underground infrastructure.



Mixed reality

Mixed reality applications for visualizing underground utilities in 3D have been available from many companies for years. A recent example that is dedicated to construction is Trimble's SiteVision. It not only enables visualizing above and belowground infrastructure, but also allows accurate measurement of positions and distances between objects.



vGIS is a visualization application that integrates traditional BIM, CAD, GIS and other types of data including Autodesk BIM and CAD models, Bentley BIM designs and Esri ArcGIS data, into augmented reality visuals. It provides users survey-grade accuracy and is accessible with consumer-grade handheld devices. It supports RTK which enables centimeter accuracy in positioning. Municipal locate services are using vGIS to visualize underground assets in an augmented reality view of the real world.

AVUS has developed an application that uses Google AR Core to project highly accurate holograms on a smartphone. AVUS compiles existing 2D and 3D records and site investigation results into a 3D model that can be visualized in augmented reality on a handheld.

Online systems for sharing location information about underground infrastructure

Several jurisdictions have developed on-line systems for sharing information about the location of underground infrastructure with stakeholders in construction projects.

Colorado

For collecting and maintaining location information about underground utilities the Colorado Department of Transportation (CDOT) has adopted a hybrid online system that incorporates elements of survey and GIS technology and practices and enables the sharing of information about underground utilities among CDOT, network operators and construction contractors. This approach enables data from disparate sources including surveys, GIS, design files, construction documents, subsurface utility engineering reports, and utility relocations into a shared database. The system was developed by a private developer Prostar Geocorp and is composed of a server application (Transparent Earth) that manages the shared database and a handheld app (Pointman) which provides access to the data in the field. The primary goal of the system is to provide easy-to-use access to high quality location data at low cost and to fit into the existing engineering and construction practices of network operators. Pointman is free and offers an affordable handheld solution for small contractors. The Transparent Earth server application is available to network operators, large construction contractors and engineering consulting firms, and government agencies such as CDOT. It enables all stakeholders in a construction project to share data about underground infrastructure.

For new and relocated underground utilities it enables all location information to be captured at survey level including the metadata typically recorded in a surveyor's field book such as when the survey was conducted, who conducted it, the equipment used, and so on. An advantage of the system is that it enables survey-grade information to be captured by survey technicians as well as GIS professionals with some additional training in survey technologies.

Montana

In Montana the online Utility Permitting Administration System (UPAS) was rolled out In January of this year. UPAS is a cloud-based system that was developed by Utility Mapping Services, Inc. and GEO.works International. Since January the location of all new underground infrastructure in the state right-of-way has been captured in UPAS. For new and relocated underground utilities it enables all location information to be captured at survey level including the metadata typically recorded in a surveyor's field book such as when the survey was conducted, who conducted it, the equipment used, and so on. The UPAS server manages the shared database in the cloud. Maps of underground utilities and other information are available over the web to any device with a browser including mobile devices.

At the completion of construction accurate as-builts must be uploaded to UPAS as electronic drawings in DGN or DWG format. Data can be 2D or 3D. For small rural coops who may not have resources for converting paper construction drawings to CAD drawings, MDT assists in the conversion. UPAS can also accept a variety of GIS data for landbase and transportation networks. Currently UPAS does not provide access to the records databases maintained by network operators. UPAS is accessible to MDT and network operators, but not directly to construction contractors, who can only access the UPAS data when contracted by a network operator.

Developments in Standards

Quality standards

In the U.S. the 2003 ASCE 38-02, which has been used many years for classifying the quality of location information about underground infrastructure and is widely seen as being out of date, is being revised. In France the 2012 presidential decree defines three explicit levels of cartographic accuracy for underground structures. In Canada the CSA S250 (2011) standard also specifies absolute precision with three different quality levels for exposed utilities and one for remote sensed detection.

ASCE Standards

ASCE 38-02, published in 2002, is intended to standardize the classification of the quality of location information about existing subsurface utility networks on engineering drawings. The standard defines four quality levels based on methods used to determine the location of underground assets.

A. Precise horizontal and vertical location of utilities obtained by the actual exposure and subsequent measurement of subsurface utilities, usually at a specific point. Accuracy is typically set to 15-mm vertical and to applicable horizontal survey and mapping accuracy as defined or expected by the project owner.
B. Information obtained through the application of appropriate surface geophysical methods to determine the existence and approximate horizontal position of subsurface utilities.

C. Information obtained by surveying and plotting visible above-ground utility features and by using professional judgment in correlating this information to Quality Level D.
D. Information derived from existing records or oral recollections.

The basic deliverable for utility information is a CAD file or plan sheet that has quality levels A, B, C, and D assigned to each asset. Quality level A data typically requires a supplemental data form with additional information. This standard does not address the quality of vertical information other than for quality level A data.

New ASCE 38-20 standard

The release of the new ASCE *Standard Guideline for Recording and Exchanging Utility Infrastructure Data* (also referred to as the *utility as-built standard*) developed under the auspices of the American Society of Civil Engineers (ASCE's) Construction Institute(CI) and Utility Engineering and Surveying Institute (UESI) is imminent. The standard draft passed committee ballot in November 2019 and in January 2020 all comments were addressed. The Open Geospatial Consortium (OGC) has already adopted the standard draft for the Model for Underground Data Definition and Integration (MUDDI) initiative.

A white paper on the new ASCE standard was published in 2018 which provided an overview of the new standard and its intended use cases. (The actual standard when it is made available publicly may differ from the white paper.) The new guidelines are targeted on two use cases;

1. capturing and recording the location of new utility data at the time it is installed and for
2. recording location data for existing utilities exposed during construction.

It is intended as non-binding guidance to assist right-of-way and utility owners in establishing their own standards. The objective of the guideline is to provide a common definition for communicating the positional accuracy of utility assets and define a minimum set of data attributes necessary to communicate the position along with the type of equipment, geometry, function, ownership, materials, status and other information for each asset. The guideline specifies essential elements for documenting the location and attributes of underground and above-ground utility infrastructure, especially for newly installed utilities and for utilities exposed during construction. It defines levels of positional accuracy of utility infrastructure.

ASCE 38-02 is not prescriptive with respect to accuracy and is generally 2D in focus, whereas more modern quality standards such as PAS 128, the French DICT, and Canadian CSA S-250 which reflect modern technical developments specify accuracy in 3D. The new ASCE standard guidelines specify positional accuracy.

The new guideline defines the elements of utility data needed to facilitate exchange of a 3D utility model with sufficient attributes for civil engineering. The guidelines also specify that metadata should be provided with all exchanged data including feature type, how and when the data was collected, the coordinate reference system and datum used, the individual(s) who certified the data, and any known limitations.This is not intended as a prescriptive data model but to indicate the minimum data elements required for civil engineering practice.

PAS 128

One of the most modern national standards is the Publicly Available Specification (PAS 128). It was developed under the auspices of the British Standards Institution (BSI) and sponsored by the Institution of Civil Engineers (ICE) and others. PAS 128 not only includes the A,B, C, D quality levels based on the ASCE standard, but extends it with explicit accuracy levels B1 to B4 for remote detection, somewhat analogous in this respect to the French decree.

PAS 128, which was aimed at locate practitioners, was initiated in 2012 and went through 3 drafts. There was a high level of participation in the industry. The first draft got 508 and the second 685 comments. The final version was published in 2014.

The PAS process is a sponsored fast track specification managed and produced by the British Standards Institution (BSI). The PAS process requires 12 to 16 months from initiation to publication and follows rules specified by the BSI. PAS128 is entirely the work of volunteers.

Historically, the development of the PAS128 standard for locating underground utilities was sponsored by many organizations in the UK including the Institution of Civil Engineers (ICE), Heathrow Airport Holdings, Highways Agency, Transport for London, National Joint Utilities Group, Ordnance Survey, University of Birmingham - School of Civil Engineering, the Utility Mapping Association and others.

The PAS128 standard has been very successful. Over 400 copies have been sold, which is exceptional for BSI publications which typically sell on the order of 200. It has been adopted by Hong Kong, El Salvador, and countries in the Middle East.

Similar to ASCE 38-02 the PAS 128 standard defines quality levels A through D based on the type of survey used to locate underground utilities.

QLD - Desktop search techniques were used to identify existing utility data by identifying known utility owners within the survey area, requesting asset information from each of them, typically as-builts, and compiling the collected information. Locational accuracy of infrastructure depicted in as-builts is generally poor.

QLC - Requires site reconnaissance to identify above-ground visible physical features that are indicative of and help locate utilities within the survey area. Locational accuracy is undefined.

QLB - For this quality level PAS requires that at least two remote sensing techniques must be used in detecting utilities. Electro-magnetic locating (EML) and ground penetrating radar (GPR) are required, but others may be used in addition. Most EML systems only detect metal, do not have the capability of digitally recording what was detected, and can only provide rough estimates of depth. GPR is able to provide 3D location, is not able by itself to identify the type of utility, and does not work well in certain types of soils such as clay. Post-processing is often used with GPR to improve the interpretation of GPR data by resolving weak and intermittent signals or distinguishing multiple targets.

In contrast to ASCE 38-02 PAS 128 breaks the QLB level into several sublevels with specified absolute precision depending on the results of remote sensing.

QLB4 - A utility cable or pipe is believed to exist but has not been detected.

Locational accuracy undefined.

QLB3 - Only the horizontal location of the utility has been detected by one of the geophysical techniques used. Locational accuracy ±500 mm (XY), Z locational accuracy undefined.

QLB2 - Horizontal and vertical location of the utility was detected by one of the geophysical techniques used. Locational accuracy for X,Y ±250 mm or ±40% of detected depth whichever is greater, for Z ±40% of detected depth.

QLB1 - Horizontal and vertical location of the utility was detected by multiple geophysical techniques. Locational accuracy for X,Y ±150 mm or ±15% of detected depth whichever is greater, for Z ±15% of detected depth.

QLA - Involves exposing the target utilities within the survey area by excavation to confirm and record the location and other attribute data. Locational accuracy for X,Y ±50 mm, for Z ±25 mm.

In contrast to the standards in some other countries PAS128 reflects the advances in underground detection technology - hardware and software - that have occurred in the last few years.

PAS 256

The PAS 256 standard "Buried services – Collection, recording and sharing of location information data" was launched in April, 2017 and was intended to complement the existing PAS 128 standard. PAS 256 sets out a data protocol to enable effective recording and sharing of the location, state, and nature of buried assets, and recommends how existing asset records should be updated, recorded and collated. It also covers the gathering of geospatial data using absolute or relative accuracy, plus associated evidence (such as photographic evidence).

Revisions to PAS 128

A number of issues that were identified in PAS 128 2014 are now being addressed in a revision to the standard. An academic study from the University of Birmingham investigated the effectiveness of the British PAS128 2014 standard for underground utilities. Test pits revealed that achieving a high vertical accuracy with remote detection

Survey type	Quality level	Location accuracy Horizontal	Location accuracy Vertical	Comments
Desktop utility records search	D	Undefined	Undefined	as recorded in as-built record
Site reconnaissance	C	Undefined	Undefined	a segment of utility whose location is demonstrated by visual reference to street furniture, topographical features or evidence of previous street works
Detection	B4	Undefined	Undefined	a segment of a utility is shown as either a QL-D or QL-C on as-builts but was not detected using either GPR or EML
Detection	B3	± 500mm	Undefined	utility is only detected horizontally with one technique
Detection	B2	± 250mm	40% of detected depth	one or both techniques (EML and GPR) have detected the utility but in different locations within the tolerance stated, or the utility was detected with just EML
Detection	B1	± 150mm	15% of detected depth	the utility has been detected using both GPR and EML in different locations within the tolerance stated.
Verification	A	±50 mm	±25 mm	horizontal and vertical location of the top and/or bottom of the utility

techniques was problematic. Furthermore, it was found that while using multiple technologies for detecting underground infrastructure significantly increased the confidence in the detected location of underground utilities it did not increase the accuracy. Other issues that have been identified and taken into account in the latest revision include; the current standard is addressed to practitioners but neglects owners/clients; the current standard assumed a 2D world, 3D and BIM need to be taken into account; whether to include post-processing of GPR scans needs to be revisited; and finally there were inconsistencies between PAS256 and PAS128.

The latest revision to the PAS 128 standard was made available for public review through March, 2020. In this revision quality levels D, C, and A do not differ materially from the earlier version, but now all Bx levels require the application of at least two detection techniques: EMI and GPR.

The 2014 version included guidelines targeted on the locate practitioner on how to use the standard. In the latest revision there are now also Annexes B and C aimed specifically at the client/owner explaining how they should use the standard.

France DICT

Project managers of proposed construction projects are required to send a DT which is a statement of the proposed work including a polygon delineating the area affected to the operators of utility networks operating in the area. In return operators of utility networks must provide the project managers maps of their underground networks in the area indicating the accuracy of the geographical location of different structures of their networks classified according to three accuracy classes.

Class A*: if the maximum uncertainty of location indicated by the utility operator is less than or equal to 40 cm*

Class B*: if the maximum uncertainty of location indicated by the utility operator is greater than that for Class A and less than or equal to 1.5 meters*

Class C*: if the maximum uncertainty of location indicated by the utility operator is greater than 1.5 meters , or if the operator is not able to provide the location.*

The Decree states that uncertainty in the geographical location of a structure is considered likely to jeopardize the construction project or significantly impact the technical or financial conditions of its implementation when the accuracy of the geolocation of the structure is classified B or C. For structures falling in these accuracy classes, the utility operator is required to initiate a process to reduce this uncertainty and achieve class A as quickly as possible.

Singapore

In August 2017 the Singapore Land Authority (SLA) released a standard and specifications for the procedure and practice of utility surveying in Singapore. The standard specifies the data that should be captured for new underground utilities including telecommunication, sewerage, water supply, electric power, gas, and drainage. It specifies that after installing utilities and prior to filling the trenches, an as-built survey should be performed by a registered surveyor to capture the location of the utilities with horizontal accuracy of ±100mm and vertical accuracy of ±100mm. It specifies that the survey equipment to be used should be a total station, GNSS Real Time Kinematic (RTK), or 3D Laser Scanning.

The standard is intended to provide a baseline to be incorporated in construction contracts and permits. Regulated by government authorities, all water, power, gas, and telecommunication companies now mandate delivery of as-built records which are captured according to the standards in new construction contracts where utilities are installed using an open trench. Additionally, since 85% of land in Singapore is owned by the state , if a major government land development agency such as the Urban Redevelopment Authority (URA) routinely incorporated this standard in its land use and development permits, it would effectively become a *de facto* nation-wide mandate.

In addition to location, the standard also defines the attribute information to be captured. For example, for an electric power cable, the standard specifies that x,y,z should be surveyed at 20 meter intervals for a straight line cable and more frequently for a curving cable. In addition, height, width, number of columns, number of rows, number of ducts, number of cables and quality level should also be captured. The quality standard used in Singapore is; 1) ±100mm, 2) ±300mm, 3) ±500mm, 4) Unknown accuracy and 5) Trenchless method. In Singapore most underground utility work is open trench, although there is some trenchless which requires gyro surveying which is currently under consideration for inclusion in the standards.

The standard does not specify the format in detail or what is to be done with the as-built information. Currently in Singapore there is nothing in place to require sharing of digital information about the underground to non-government entities like The Netherlands' BRO or the

UK’s National Underground Asset Register (NUAR) project. The Digital Underground project initiated by the Singapore Land Authority aims to establish a reliable national digital twin of subsurface utilities in Singapore. After conclusion of an initial roadmapping phase, the project is currently exploring and developing the cornerstones of an ecosystem (e.g. policy levers, data stewardship, human resources, data management architecture and infrastructure) to collect and manage the quality of subsurface utility data and make it available for planning and land administration purposes. As part of this process, the Singapore’s utility surveying standards will be evaluated, improved and extended. Their future increment may incorporate additional utility surveying technologies and scenarios (e.g. trenchless) and the specification of a standard for the delivery of as-built information that enables verification and data lifecycle management as part of a national digital twin.

Canada

In Canada the purpose of the Canadian Standards Association CSA S250 Standard from 2011 is to specify the mapping records requirements used to identify and locate underground utility infrastructure. This Standard is intended to promote the use and drive the advancement of mapping records during the planning, design, construction, and operation of underground utility infrastructure. Impetus for the widespread adoption of S250 could be provided by a Senate Bill S-229 that is currently before the House of Commons that opens the door to a digital system (similar to the Dutch KLIC and Flanders KLIP) that does not require an operator to actually visit planned excavation sites by providing digital maps instead.

The standard defines levels of accuracy for recording the location of underground infrastructure when the infrastructure has been exposed either by potholing or during excavation.

- **Record accuracy level 0** — There is no information available related to spatial accuracy. The position as shown on the drawings is the best possible estimate of the actual location.
- **Record accuracy level 1** — For exposed infrastructure. Horizontal and vertical location of underground utilities shall be measured while exposed and recorded in a real world coordinate system by a competent individual. Accuracy ± 25 mm in the x, y, and z coordinates.
- **Record accuracy level 2** — For exposed infrastructure. Horizontal and vertical location of underground utilities shall be measured while exposed and recorded by a competent

individual. Accuracy ± 100 mm in the x, y, and z coordinates,

- **Record accuracy level 3** — Horizontal and vertical location of underground utilities shall be measured while exposed and recorded by a competent individual. Accuracy ± 300 mm in the x, y, and z coordinates.
- **Record accuracy level 4** — For exposed infrastructure. Horizontal and vertical location of underground utilities shall be measured while exposed and recorded by a competent individual. The measurements shall be tied into either a relative feature or geodetic datum. Accuracy ± 1000 in the x, y, and z coordinates.
- **Record accuracy level 5** — For infrastructure that has not been exposed. Location measured and recorded by a competent individual using geophysical methods. These less precise measurements shall be tied to either a relative feature or geodetic datum. Accuracy ± 1000 mm in the x and y coordinates. Accuracy of the z coordinate is not quantified.

Furthermore, the standard states that if the criteria for accuracy level 0 to 5 are not used, the owner is referred to other standards, specifications, or instructions from the utility. The A, B, C, D quality levels of the American Society of Civil Engineers (ASCE) 38 standard for underground infrastructure are explicitly referenced for this purpose.

Heathrow

Heathrow's confidence codes are a way of classifying the results of underground utility detection, verification and location undertaken by different survey methods:

- D – Desktop survey followed up with site reconnaissance.
- C – Use of underground scanning tools to locate services with a reasonable degree of confidence of what has been located.
- B – Detection - Use of two techniques to verify the location of the utility, for example, using Ground Penetrating Radar (GPR) to confirm the location found with an electromagnetic scanner.
- A –Verification - Digging a trial hole using a vacuum excavation/air pick or hand tools to expose the service, then surveying the location to 25mm accuracy.

Heathrow has been a major contributor to the development of the PAS128 standard for underground infrastructure. PAS 128 is aimed at the practitioner, surveyors who make their living detecting and reporting the location of underground utilities.

Heathrow has also supported the HSG47 guide *Avoiding danger from underground services* which is aimed at all those involved in commissioning, planning, managing and carrying out work on or near underground services. It outlines the potential dangers of working near underground services and gives advice on how to reduce any direct risks to people's health and safety, as well as the indirect risks arising through damage to services.

Standard for sharing data

The Open Geospatial Consortium's (OGC) underground information initiative *Model for Underground Data Definition and Integration*, with the appropriate acronym MUDDI, is intended to provide an open standards-based way to share information about the below ground. The MUDDI project has identified several different broad use cases that the model is intended to support including routine street excavations (EX), emergency response (ER), utility maintenance programs (OM), large scale construction projects (AE), disaster planning and response (DP), and smart cities programs (SC). For each of these, several basic requirements that the model needs to satisfy have been identified. For street excavations the requirement is location of all entities with high horizontal, medium vertical accuracy (2.5D) of underground infrastructure; for large construction projects, detailed 3D geometry of underground infrastructure and detailed 3D geology; for emergency response, interdependencies between different networks; for utility maintenance, network topology and facility location and condition; and for smart cities the ability to monitor and relate streams of data from sensors.

To provide a way for the model to be used by different types of users, the concept of profiles has been introduced. Profiles have been used for other OGC standards and allow for different levels of complexity for different domains and applications. The proposed profiles include asset, excavation, emergency, planning and integration profiles.

The MUDDI model is intended to build on and be compatible with many existing reference/target models. The draft of the ASCE *Standard Guideline for Recording and Exchanging Utility Infrastructure Data* (also referred to as the *utility as-built standard*) has been adopted for the MUDDI initiative. MUDDI also draws on OGC Standards relevant to the built environment, such as CityGML and LandInfra and OGC standards for modeling the natural environment such as GeoSciML and WaterML2.

A new OGC Standards Working Group (SWG) is currently being formed. The MUDDI Standards Working Group will standardize a conceptual model, a modular framework, one or more logical models, one or more implementation specifications, and mappings to/from other models for geospatial data that represent underground infrastructure assets and characterize the underground environment that contains those assets.

- The conceptual model will provide a general basis for interoperability between multiple MUDDI implementations and encodings.
- The modular framework will support extensible model capabilities as they are needed to meet specific use cases
- Each logical model will be consistent with the conceptual model and provide a more specific level of interoperability between two or more implementation standards and/or encodings.
- Each implementation specification will support a specific data language and encoding, such as GML, CityGML, or SF-SQL.
- Mappings between MUDDI and other relevant models such as LandInfra or BIM / IFC (Building Information Model / Industry Foundation Classes) will support maximum reuse of data between different domains of application and computing environment

Once the SWG is established, the objective is to develop a candidate standard within one year.

Statistical basis for assessing impact of underground utility damage

Reliable metrics make it possible to assess the social and economic impact of incidents and the effectiveness of new technologies and policies in preventing and reducing the severity of these incidents. As a model in the U.S. commercial airline industry there have been reliable statistics since the early 20th Century. In 1929 there were 51 commercial airline incidents, which represents an accident rate of about 1 for every 1,000,000 passenger miles. If that rate is prorated to the current total number of revenue passenger miles this would be equivalent to 7,000 fatal incidents per year. More recently measures continue to be taken to reduce the risk of accidents. Fatal accidents per million flights in 2018 have decreased 16 fold since 1970, from

6.35 to 0.39, and fatalities per trillion revenue passenger kilometers (RPK) decreased 54 fold from 3,218 to 59 in 2018. For the most recent two decades major commercial airline incidents in the U.S. resulted in 403 fatalities (excluding 9/11). Very good data is collected and is accessible about individual airplane incidents that help the Federal Aviation Authority (FAA) and others determine the causes of airline incidents such as the recent Boeing 737 Max 8 accidents and implement measures to continue to reduce the risk of accidents in the future.

For underground utility damage the quality of statistics varies considerably among countries. This is a summary of the available statistics.

Organization	Country	Year	Source	Networks	How compiled	Reported number of incidents of damage
Common Ground Alliance	United States	2018	Voluntary reporting	All underground utility and telecom networks	Centralized	509,000
PHMSA	United States	2018	Mandatory reporting	Gas and hazardous liquid pipelines	Centralized	636
KLIC	Netherlands	2018	Mandatory reporting	All underground utility and telecom networks	Centralized	41,169
Japan Construction Industry Association	Japan	2016	Mandatory reporting	All underground utility and telecom networks	Distributed	134

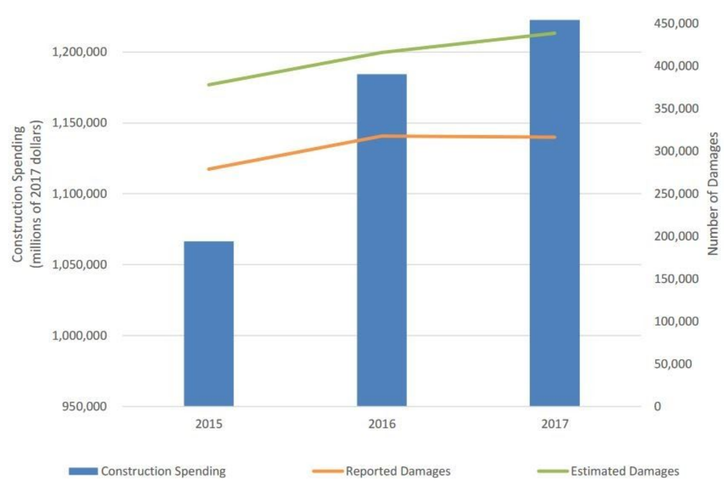
US

In the United States two different mechanisms have been adopted to collect statistics on damage to underground infrastructure. The Common Ground Alliance (CGA) collects voluntarily submitted information on incidents of underground utility damage. In contrast, federally regulated pipeline operators are required by law with the threat of serious civil penalties to report incidents of pipeline damage and leaks to the Pipeline and Hazardous Materials Safety Administration (PHMSA). The annual CGA DIRT and PHMSA reports provide statistics for underground utility damage. However, they do not report statistics on casualties, and only collect data on direct costs, not on indirect and social costs.

Common Ground Alliance

Officially formed in 2000 the Common Ground Alliance (CGA) has been collecting voluntarily submitted statistics on underground utility damage since 2003. CGA is a member-driven association of 1,700 individuals, organizations and sponsors in every facet of the underground utility industry including excavators, locators, road builders, electric, telecommunications, oil, gas distribution, gas transmission, railroad, one call centres, public Works, equipment manufacturing, state regulators, insurance, emergency services and engineering/design

The first *Damage Information Reporting Tool* (DIRT) Report was released in 2004. Since then the number of incidents of underground utility damage voluntarily reported to the Common Ground Alliance has increased. The DIRT Report for 2018 shows that the total estimated damages in the U.S. increased from 439,000 in 2017 to 509,000 in 2018, representing a 16% increase. However, those knowledgeable about the construction industry would not be surprised if the DIRT reports underestimate the total of incidents by a factor of 2X.



For trends over time the CGA breaks out incidents that are reported by "consistently reporting sources" which are sources that have reported incidents in 2016, 2017, and 2018. The CGA believes that these consistently reporting sources can be used reliably to determine temporal trends in the DIRT data. Comparing these data with a proxy for the amount of construction reveals no indication that the number of incidents is trending downward. Incidents of utility damage per million dollars of construction spending (2017 constant dollars) actually increased from 0.359 in 2017 to 0.392 in 2018.

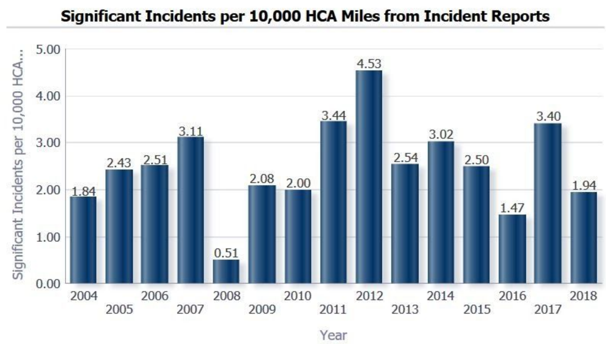
Pipeline and Hazardous Materials Safety Administration (PHMSA)

On June 10, 1999, a gasoline pipeline operated by Olympic Pipeline Company exploded in Bellingham, Washington. Three people died in the accident. On August 19, 2000 a natural gas pipeline owned by the El Paso Corporation exploded near Carlsbad, New Mexico killing 12 people. After these incidents the government moved quickly to improve the quality of geospatial and other data about underground pipeline assets. Operators were required to identify high consequence areas (HCAs) where there were 20 or more structures intended for human occupancy within a radius (potential impact radius or PIR) defined by the diameter and pressure of the pipe.

Pipeline operators are required to submit performance measure reports to the Pipeline and Hazardous Materials Safety Administration (PHMSA) for pipeline infrastructure covered by integrity management (IM) programs. This includes gas distribution, gas transmission, and hazardous liquids pipelines. In addition Gas and hazardous pipeline operators are required to report incidents of pipeline leaks and damage to PHMSA including location, volume of product released, number of fatalities and injuries, costs and cause. Failure to do so carries the threat of civil penalties.

Since 2004/2005 PHMSA has been reporting annual statistics on leaks and damage to pipelines. PHMSA defines serious incidents as those that include a fatality or injury requiring in-patient hospitalization. At first sight PHMSA statistics suggest there may have been a reduction in the number of serious incidents, but propagating these statistics to increased pipeline mileage does not support this. Furthermore, one of PHMSA's reported statistics is the number of significant incidents per 10,000 HCA miles. Significant incidents are defined as incidents involving a fatality or injury requiring hospitalization, $50,000 or more in total costs measured in 1984 dollars, substantial liquid releases, or fires and explosions. PHMSA statistics reveal no trend in improvement in this statistic.

Since 2005, pipeline operators have reported excavation damage as the cause of 1052 incidents, resulting in 48 fatalities, 195 injuries requiring hospitalization, and $ 481,736,551 of property damage. Since pipeline incident data began to be collected the proportion of incidents attributed to excavation has increased.



By analogy with the civil aviation industry, reliable statistics resulting from government mandated reporting of pipeline incidents provides the foundation for the next phase of implementing safety management plans designed to produce continuous improvement in these statistics. Safety management systems tailored to specific industries and requirements have been developed often involving regulation for civil aviation, international maritime shipping, and the rail industry in Canada. Pipeline safety management systems (PSMS), specifically the RP 1173 framework developed by the American Petroleum Institute (API) in partnership with PHMSA, state pipeline regulators, and other interested stakeholders provides best practices for pipeline operators including operational controls, risk management, incident investigation, evaluation, and lessons learned, and safety assurance. This is intended for operators of hazardous liquids and gas pipelines under the jurisdiction of the US Department of Transportation. It provides for the comprehensive and systematic management of safety-related activities for achieving its goal of zero incidents per year.

Ontario

The key metrics that are used by Ontario Regional Common Ground Alliance (ORCGA) and Ontario One Call are the number of incidents per notifications and the number of incidents per information request. Requests are to Ontario One Call

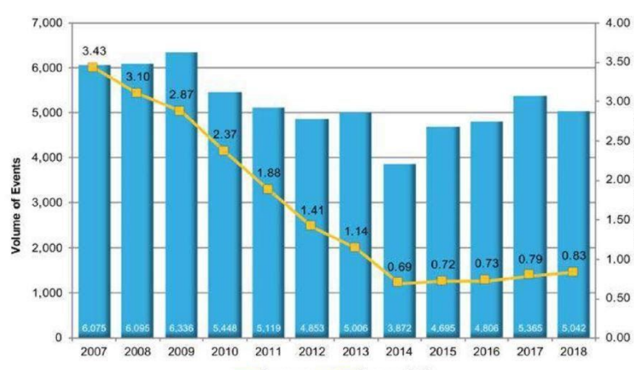


Figure 17: Damage Ratio- Damages/1000 Notifications

and originate from excavators planning to dig. Notifications go to network operators originating from Ontario One Call in response to requests.

The damage ratio for the number of incidents per 1000 notifications since 2007 reveals a decreasing trend through 2014. Since then the trend has been gradually increasing. Similarly the trend in the number of incidents per 1000 requests also decreased from 2009 through 2014, but the trend has been increasing since 2014. The 2018 damage to request ratio shows a decrease apparently reversing an upward trend from 2014. This is the result of a change in the Ontario One Call process which reduced notifications by 10%.

United Kingdom

About 4 million excavations are carried out on the UK road network each year to install or repair buried utility pipes and cables. The problems associated with inaccurate location of buried pipes and cables are serious and are rapidly worsening due to the increasing density of underground infrastructure in major urban areas.

There are over 10,000 works (construction projects) taking place every day across the UK with tens of thousands of incidents of underground utility damage during excavation occurring annually. But there are no reliable statistics on this important safety and economic issue.

A key dataset in the UK relating to major pipeline incidents is maintained by the United Kingdom Onshore Pipeline Operators' Association (UKOPA) whose members operate a network of pipelines over 27,000 km in length. There is also information relating to injuries and fatalities during construction maintained by the Health and Safety Executive. This covers a subset of underground incidents, but reporting is mandatory.

A very important recent initiative in the UK is the Utility Strike Avoidance Group (USAG) which began collecting information about underground utility strikes during construction in 2013. Like the CGA the USAG also operates on a voluntary basis with no direct funding other than support from member organizations. USAG has just released the *2017 & 18 Utility Strike Damages Report*. For this biennial report USAG analyzed reports on 3000 incidents of underground utility damage or strikes submitted by 34 USAG members. The information submitted on each incident includes when the strike occurred, where the strike occurred, how the asset was damaged (equipment type), what the damage was, type of asset damaged, type of construction project, and what caused the damage.

One of the interesting analyses in the USAG report is the cause of underground utility strikes. Respondents are requested to identify the cause of the damage from a list of over 15 possible sources.

1. Inadequate excavation procedures (Inattention/lack of awareness, Not following procedure, No protective systems, Clearance not maintained, Misuse of tools/equipment, Lack of supervision, Excavation practices not sufficient, Service markup not maintained,)
2. Insufficient survey practices (Insufficient survey practices (use of locating equipment), Inadequate survey)
3. Inaccurate and missing underground utility location information (Inaccuracy of plans, Assets not on relevant plans)
4. Inadequate work planning (Inadequate assessment of works, Insufficient time allowed)
5. Insufficient skills (Insufficient competency, Insufficient gang skills)

Since most of these incidents were reported to USAG by contractors, it may be expected that over 50 % of the causes identified are related to excavation practices. The next highest cause is missing or inaccurate location information followed by insufficient survey practices. Together these locate issues represent the second largest reported cause of strikes in both 2017 and 2018.

Researchers at the University of Birmingham analyzed 3,348 incidents of damage to underground utilities with some interesting results.

- Of 255 incidents where pre-excavation locate scans had been carried out, in 52% of the cases the utility had been detected before the strike.
- Of 187 incidents where utility plans/drawings (as-builts) had been reviewed before excavation, in 48% of the cases the utilities hit were shown on the plans.
- Of 89 incidents where the plans/drawings (as-builts) showed the utility, in 84% of the cases respondents reported that the location of the utility was inaccurately plotted. 16% said it was accurate.

In other words even when it is known that there is utility infrastructure underground, there is still a very significant risk of hitting it - perhaps because its location is not known accurately enough.

It also provides further evidence that, in general, as-builts cannot be relied on, either because they are "as designed" or because they have not been maintained and do not record modifications that may have been made since the infrastructure was first built.

Netherlands

Network operators are required to participate in the KLIC system, which is similar in some respects to one call center in North America. They are required to report all incidents of damage to their infrastructure including location, cause and other information. Based on this and other information Kadaster publishes an annual report with statistics on underground utility damage.

Network operators/managers	1,130
Annual requests for information (2018)	759,000
Annual excavation damage (2018)	41,169

Analysis of Kadaster's statistics reveal that the goal of reducing excavation damage has not yet been reached.

Japan

A survey was performed to compile national statistics about excavation damage in 2016. Of 180 network operating companies surveyed 107 responded by reporting damages experienced to their networks in that year. The respondents reported a total of 134 incidents of damage to underground utility assets like cables and pipelines and 82 incidents of damage to above ground structures.

Number of information requests 2016	*263,000*
Number of companies contacted	*180*
Number of respondents	*107*
Underground utility damage in 2016	*134*
Above-ground utility damage in 2016	*82*

These statistics are reported to be declining since data began to be collected in 1983.

Liability for underground utility damage

It has been argued that liabilities may be the single most important key to improving the quality of location information about underground infrastructure. If a formula could be found for sharing liabilities between government, excavators and network operators, it would motivate all players to implement procedures to remove the risks associated with underground infrastructure during construction. One of the reasons that utility network owners such as gas, electricity, and water distribution companies and telecommunications operators have not been motivated to improve the quality of the location information about their infrastructure is the current liability model in the construction industry which generally makes excavators liable for any damages. The bury and find approach that characterizes many jurisdictions provides little motivation for network operators to ensure the quality of their information about the location of their network assets. Liabilities in this context refers to who is responsible when an underground cable or pipe is hit during an excavation. The North American regulatory framework is in contrast with the French model where the liability model motivates network operators to improve the quality of the information about the location of their underground infrastructure.

As an example of a simple liability model for damage to underground infrastructure, several years ago at a GITA ANZ event in Brisbane a simple, but interesting liability model for Queensland water infrastructure was proposed. When a utility or a contractor (employed by a network operator) completes a job installing or maintaining underground facilities, they are required to submit accurate as-builts. The next time there is an excavation in the same area, those as-builts are provided to the excavator. If there is utility damage during excavation, the liabilities would work as follows: if the as-builts were accurate, then the damage is the excavator's responsibility, if the as-builts were not accurate, it is the utility's contractor's responsibility. In this example there is a strong motivation for contractors to provide as-builts showing the location of the underground facilities they installed or maintained that are accurate and up-to-date to avoid liabilities for any subsequent damage.

North America

Florida

In North America regulation works in a very different way. Florida is characteristic of North America. The Underground Facility Damage Prevention and Safety Act enacted in 2017 by the Florida legislature is typical of the legislation creating state one-call or call-before-you centers. It mandates that every organization with underground infrastructure is required to be a member of the state one-call centre, which is supported by members. Each utility has to provide information to the center about the service area where they might have underground facilities. They are also required to provide underground locate services. This can be quite expensive because it typically involves dedicated staff and an investment in underground detection equipment and vehicles. Under this system excavators are entitled to locate information at no cost.

If an excavator does not call the state one-call centre and hits a utility, the excavator is liable for all costs, therefore excavators for industrial, commercial and public (but often not residential) construction projects generally contact the one-call centre prior to digging. The excavator provides the rough location and depth of the proposed excavation and when they plan to begin work. Since the one-call centre does not maintain maps of underground infrastructure, when an excavator contacts them, they contact all utilities whose service territories overlap the planned excavation and pass on the information about the proposed excavation.

In Florida the utility operator has two days to come to an excavation site to mark using stakes, paint or flags where they believe their facilities are. The Florida act stipulates that these markings identify a corridor 4 feet wide within which a utility cable or pipe is expected to be found and that they conform to a standard for colour code for markings. The law also provides an option for a utility operator to state that it believes it has facilities in the area but is unable to identify where they are. This option is only available for abandoned facilities or for facilities that are not detectable with the available technology.

Typically each utility and telecom operator contacted will dispatch locate staff equipped with current as-builts, electromagnetic and/or ground penetrating radar scanners to detect and mark where their networks traverse the site. After all the network operators with facilities in the areas have done this, the excavator is free to begin excavation. If a network operator has stated that it can't identify the location of its facilities, the Florida act requires the excavator to use underground detection tools to try to identify any underground facilities. The excavator is free to dig outside the marked utility corridors. To dig within the corridors, the Florida act stipulates that soft digging techniques must be used.

Liabilities work as follows:

- If after the network operators identify the location of underground facilities, an excavator causes damage, the excavator is liable for the total sum of the losses to all parties involved to a maximum of $500,000 per underground network.
- If a network operator does not mark the location of its facilities after being contacted by the One-Call system and an excavator damages the underground network, the excavator is not liable for the damage and the network operator is liable for any any injury to a person or to equipment to a maximum of $500,000.
- If the network operator isn't able to identify the location of its facilities in the excavation area, the excavator is not liable for any damages that might occur.

But there is a proviso on this: An excavator must excavate in a "careful and prudent manner, based on accepted engineering and construction practices, and it does not excuse the excavator from liability for any damage or injury resulting from any excavation or demolition." Furthermore, if the network operator is unable to identify the location of its facilities in the excavation area, the act stipulates that the excavator must use subsurface detection tools to try to identify the location of the infrastructure.

At a high level the liabilities are pretty straightforward, but in practice there is plenty of room for litigation. A recent example of what can happen when unknown utilities are encountered during construction is the 405 Freeway widening project in Los Angeles where workers had to remove nine miles of unexpected utility lines which contributed to delaying the project a year behind schedule and resulted in a $400 million lawsuit.

The other important aspect of this legislation is that it does not require the information discovered about underground utilities to be shared. It is not the responsibility of the one-call centre itself to manage this type of information. The act does not mention maps, paper or digital, to be provided by the network operators nor does it require utility location information discovered by the excavator to be shared with the network operators. Over time there is little in this act that would lead to an improved map of underground infrastructure.

Furthermore, The North American model often results in unnecessary utility relocations. For example, in the traditional approach to highway design, the designer ignores utilities during design. After design and right-of-way acquisition, the one-call center would be notified and the affected utilities would mark the location of their utilities. If utilities conflict with the design, they would have to be relocated. As a result utilities are routinely relocated, often at great expense and often unnecessarily. A better approach is to design the highway in a way that takes into account where utilities are located to minimize relocations. But this requires accurate maps of underground utilities during the planning and design phase, not just prior to construction.

Colorado

In 2018 the Colorado legislature revised its one-call legislation. The latest legislation is progressive. It explicitly mandates subsurface utility engineering (SUE) prior to engineering design for public civil engineering projects to determine the 2D location of underground utilities to ASCE 38 quality level B by a licensed professional engineer. (ASCE quality level B requires the application of remote sensing detection technologies such as electromagnetic detection and ground penetrating radar. Prior to the commencement of construction in addition to painting or flagging a proposed excavation site, infrastructure owner/operators are required to provide a digital sketch, a hand-drawn sketch, or a photograph. It puts some degree of onus on owner/operators to provide accurate information about the location of their underground facilities.

In Colorado Article 1.5 appears to alter this general liability model. It states that if the documentation or markings are determined to be inaccurate, the excavator shall immediately notify the owner/operator through Colorado 811 to request an immediate reverification of the location of underground facilities by the owner/operator. The owner/operator is required to respond as quickly as practicable during which time the excavator can continue excavation activity with appropriate caution. Furthermore, Article 1.5 states that if the documentation or markings provided still fail to identify the location of the underground facilities, the excavator is required to notify Colorado 811, but can then proceed with excavation. Article 1.5 states that in this case the excavator is not liable for damage to the owner/operator's facilities except upon proof of the excavator's lack of reasonable care. However, accuracy is not quantified. Later in Article 1.5 where liabilities are discussed, the language relating to accuracy seems less strong. It states that excavators are liable if they fail to notify Colorado 811 of their intention to excavate or fail to exercise reasonable care in excavating. Owner/operators are liable if an underground facility is damaged as a result of the owner/operator's failure to participate in Colorado 811 or by their failure to use "reasonable care" in the marking of the damaged underground facility.

Calgary

For a number of years the City of Calgary has had a bylaw that defines how a network operator can access City rights-of-way such as roads for purposes of constructing, maintaining or operating its equipment including telecommunication, electrical, natural gas, steam, water wastewater and stormwater facilities and pipelines.

Years ago the City of Calgary, in a very forward looking move, passed an ordinance that required all utilities and telecoms operating within city limits to share maps of their underground networks as part of Joint Utility Mapping Partnership (JUMP). The maps had to be submitted in digital form, DGN files at the time. Under the impetus of the city ordinance, the electric power utility decided to change their facilities records workflow to improve the quality and timelines of their data so that the maps they made available through JUMP were accurate and up-to-date. To do this required changing the data flow from network engineering to their GIS. All of their engineering data was stored in a spatially-enabled relational database which enabled them to shorten the cycle from engineering to GIS and ensure that records backlogs were very short, on the order of a day. One of the important benefits of JUMP and the improved data workflow was that the utility reduced its fleet of more than 20 locate vehicles to two, freeing up staff for other activities and saving several hundred thousand dollars annually.

The unique and interesting parts of this bylaw relate to new infrastructure. It requires submission of electronic as-builts by network operators, provides for on-site inspections to verify the as-builts, and assigns costs and liabilities for underground equipment whose location as reported in as-builts is unreliable.

The bylaw requires that each network operator submit as-built drawings in electronic format, typically DWG files, to the City within 60 calendar days following completion of installation of its equipment on a public right-of-way. The as-builts are required to comply with two key provisions

1. The equipment is less than 35 centimeters horizontally and vertically from the centre line approved in the *utility alignment permit*
2. It adheres to the CSA S250 quality standard.

The City reserves the right to carry out on-site inspections the cost of which is shared between the network operator and the City. The network operator is required to give the City 3 days' notice prior to completion of work to allow for scheduling of the inspection. If during an inspection (or at any other time) the City identifies deficiencies in the network operator's compliance, the City can declare the equipment non-compliant. The City can then take steps to ensure the network operator does whatever is necessary, at the network operator's cost, to bring the equipment into compliance. Specifically a network operator must pay for 100% of the direct costs for relocations of non-compliant equipment as well as indirect costs including any damages, liabilities, re-design costs and associated delay costs incurred by other participants in a public right of way resulting from the network operator's non-compliant equipment.

In addition to improved safety to the public and construction workers, there is a financial motivation for a utility or telcom to improve the quality of its mapping of underground infrastructure. Not an insignificant cost incurred by a utility supporting this liability structure is the maintenance of a fleet of asset locate vans, equipment and staff. A utility can reap significant cost savings by reducing the size of this fleet by improving the quality and timelines of the information about the location of their underground infrastructure. For example, the power utility in Calgary, Alberta maintained over twenty vans dedicated to cable locates.

In spite of these motivations for better information about the location of underground infrastructure, the liability structure in North America, which effectively limits the risk to operators, has historically not provided a strong motivation for utility or telecom operators to implement procedures to improve the quality of their information about the location of their underground network facilities.

France

It is interesting to contrast this legal structure with that in France as laid out in the 2012 Presidential Decree on critical infrastructure. Project managers of proposed construction projects are required to send a statement of the proposed work including a polygon delineating the area affected to the operators of all utility networks operating in the area. In return network operators must provide to the project manager maps of their underground networks in the area indicating the accuracy of the geographical location of different structures of their networks classified according to three accuracy classes.

- Class A: if the maximum uncertainty of location indicated by the utility operator is less than or equal to 40 cm
- Class B: if the maximum uncertainty of location indicated by the utility operator is greater than that for Class A and less than or equal to 1.5 meters
- Class C: if the maximum uncertainty of location indicated by the utility operator is greater than 1.5 meters , or if the operator is not able to provide the location.

The Decree states that uncertainty in the geographical location of a structure is considered likely to jeopardize the construction project or significantly impact the technical or financial conditions of its implementation if a facility is classified in accuracy classes B or C. If a facility is classified as B or C, the excavator is required to carry out further investigation to locate it. The Decree specifies that the cost of the investigation is to be shared between the excavator and the network operator according to the following rules:

- The excavator assumes the entire cost when the structures are assigned by the operator to accuracy class B and further investigation reveals that the actual classification is found to be Class B or Class A
- Half of the cost of the investigation is to be borne by the operator when the structures are assigned by the operator to accuracy class C
- All of the cost is to be borne by the operator when the structures have been assigned by the operator to accuracy class B and when the result of further investigation reveals that the actual classification is accuracy class C

The decree requires that any improved location information discovered by the excavator must be shared with the network operator. As a result over time it would be expected that the number of facilities classified as B or C would decline. If many of an operator's facilities were classified as C or B the financial outlay for sharing the cost of excavators to locate underground utilities for a large number of construction projects could become substantial. This would be expected to provide a strong motivation for network operators to improve the quality of the location information about their facilities. Another important advantage of the French system is that it specifies maps must be provided which means that information about underground utilities would be available to developers during planning and design which reduces the number of unnecessary utility relocations.

Role of surveyors in underground locating and mapping

Accurately mapping underground utility and telecom network assets represents a growing opportunity for professional surveyors. In order to ensure continuing improvement in the accuracy of location information about underground utilities, some international jurisdictions are requiring that new or modified underground infrastructure be surveyed by a registered surveyor. Technical advances are making it easier for surveyors to conduct underground surveys. For construction projects owners, engineers and contractors are increasingly recognizing that surveyors who can offer a combined above- and below-ground survey are able to add significantly more value than the traditional above-ground-only survey.

Technical advances enable surveyors to conduct underground surveys

Underground locate practitioners use all the information that is available to them including as-builts (however unreliable), site surveys, remote sensing tools such as electromagnetic induction, ground penetrating radar, and other techniques, and potholing.

Until recently GPR has remained the preserve of highly trained geotechnical and other underground engineering professionals. A major inhibitor to broader use of ground penetrating radar for detecting the location of underground utilities is the difficulty in interpreting radar scans. Non-geotechnical professionals including surveyors found it a challenge to interpret GPR scans consisting of images with hyperbolas showing the reflections of RF waves from underground objects. In 2019 Leica Geosystems released the DSX ground penetrating radar system that is the first to address this gap in a compact, portable system. A key feature of the DSX GPR device and DXplore software is analytics to interpret the GPR scans and visualize underground infrastructure in the form of tomographic images, rather than radar hyperbolas. A semi-automated process uses software to identify the location of underground cables and pipes. The resulting 3D model can be exported as a 2D or 3D vector file in a CAD compatible file format. This may not be useful for experienced GPR practitioners. Geotechnical experts are trained to work with B-scan/radargram data representation and interpretation. But for surveyors and others who don't have GPR experience and recognize that underground surveying represents a significant business opportunity, this represents a way to incorporate underground surveys underground into their practice.

Requiring a survey crew to be on-hand throughout an excavation to survey exposed utilities can be cost prohibitive. A research project by Costain and Bentley found that accurately surveyed control points enabled photogrammetry using a consumer grade smartphone to be used to generate a 3D model of comparable accuracy to a traditional survey and much more cost efficiently.

Capturing accurate locations for new underground infrastructure

In order to ensure continuing improvement in the accuracy of location information about underground utilities, some international jurisdictions require that new or modified underground infrastructure be surveyed by a registered surveyor.

Montana

In 2019 the Montana Legislature enacted Senate Bill 76 which revised the laws relating to the occupancy of utilities on state highway rights-of-way. The bill allows the department to issue occupancy permits for installation, construction, maintenance, repair, or system upgrade of all utilities on state highways. Under this legislation the Montana Department of Transportation (MDT) implemented a new rule governing *Electronic Utility Permitting for Right-of-Way Occupancy*.

The rule requires that an "as built" survey showing the location (to survey grade) and other attributes of newly installed utility facilities must be submitted electronically to the MDT within 90 days of completion of construction. The new rule has teeth. It specifies that the as-built survey must be certified by a licensed professional engineer (PE) or professional land surveyor (PLS). Alternatively the as-built survey can be certified by an authorized officer of the utility owner. However, in this case the MDT reserves the right to conduct an audit and inspection to verify the accuracy of the as-built. All costs associated with this inspection are to be borne by the utility owner.

Canada

A Professional Surveyors Canada report recommends requiring that all new underground infrastructure be surveyed and mapped in 3D with high precision and reliability and sharing basic information on the type, location and depth of underground infrastructure in a standardized form through a common, accessible system. It is also recommended that all underground infrastructure surveyed should be in a common format that can update a master map/GIS data set.

Singapore

In Singapore the standard guidelines for new installations of underground infrastructures specify that new underground assets should be surveyed by a registered surveyor using one of a few specified techniques. The responsibility for engaging the surveyor and eventually submitting as-built data is usually with the utility development contractor. The standard specifies the data that should be captured for new underground utilities including telecommunication, sewerage, water supply, electric power, gas, and drainage. It specifies that after installing utilities and prior to filling the trenches an as-built survey should be performed by a surveyor registered at the Land Surveyors Board of Singapore to capture the location of the utilities with horizontal accuracy of ±100mm and vertical accuracy of ±100mm. It specifies that the survey equipment to be used should be a total station, GNSS Real Time Kinematic (RTK), or 3D Laser Scanning. The standard does not specify format or what is to be done with the as-built information.

France

In France, contractors are required to survey all new and changed underground structures. These surveys must satisfy certain conditions. Location coordinates of structures in an open trench must be surveyed by a certified surveyor. If remote detection technology such as GPR is employed, the firm performing this work is not required to be certified, but a certified surveyor must be involved in georeferencing the data. Whatever the method of measurement used , direct or remote, the accuracy of the locations of new or changed structures reported by the contractor must be accuracy class A, in other words 40 cm or better. For each structure the data recorded must include the name of the project manager of the site, the name of the company that provided the location information, the name of the certified surveyor responsible for determining the location of each structure, the maximum measurement uncertainty (for x, y, and z), and in the case of remote detection such as GPR or EMI, the type of measurement technology used.

Bern, Switzerland

Bern, Switzerland has instituted regulations to ensure that accurate data is captured for new construction projects involving underground infrastructure. For example, there is a 24 hour rule that requires a contractor to notify the city survey department 24 hours before closing a trench. For large projects city surveyors periodically verify surveys of underground works.

Rotterdam, The Netherlands

Similar regulations exist in the Municipality of Rotterdam in The Netherlands. The contractor is required to notify the city's Underground Bureau before closing a trench in order to enable inspection (in particular, verification of the utility being built according to plan) and survey by the municipality for inclusion of as-built data into their own records. The municipality of Rotterdam engages private surveying companies on long-term contracts in order to conduct the jobs within 24 hours of the notification.

Calgary, Alberta

The City of Calgary has legislated a by-law that is designed to share information about underground utilities and improve the quality of this information. The by-law requires all network operators with underground infrastructure under public rights-of-way to submit to the city electronic as-builts showing the location of newly installed network equipment. The bylaw requires that each network operator submit digital as-built drawings to the City within 60 calendar days following completion of installation of its equipment on a public right-of-way. The as-builts are required to comply with two key provisions

- The equipment is less than 35 centimeters horizontally and vertically from the centre line approved in the utility alignment permit
- It adheres to the CSA S250 quality standard.

Furthermore, the City reserves the right to carry out on-site inspections to verify submitted as-builts the cost of which is shared between the network operator and the City.

Conclusion

In order to ensure continuing improvement in the accuracy of location information about underground utilities, international jurisdictions are requiring that new underground infrastructure be surveyed by a registered surveyor. Technical advances are making it easier for surveyors to conduct underground surveys. For construction projects owners, engineers, and contractors are increasingly recognizing that surveyors who can offer a combined above- and below-ground survey are able to add significantly more value than the traditional above-ground-only survey. Surveyors who offer combined above and below ground surveys are finding that a combined offering increases their profit margins.

Improving the accuracy of locations of existing underground infrastructure

Surveyors may also have a role in improving the accuracy of the location of underground infrastructure. In many jurisdictions, location data for existing underground infrastructure is inaccurate, out-of-date and incomplete. There are several ways that surveyors could contribute to improving the locational accuracy for existing infrastructure.

One of the most important roles for surveyors is accurately capturing the location of underground infrastructure exposed during excavation. However, having a survey crew on site throughout an excavation is often uneconomical, which is the reason why Costain and Bentley conducted an experiment that only required surveyors to capture accurate locations for control points at the beginning of excavation. Then when underground utilities were exposed during subsequent excavation, smart phones could be employed to photograph exposed infrastructure together with control points. Costain was able to show that locations captured this way achieved the same accuracy as a direct survey of exposed utilities.

Another way that surveyors can contribute to improving the locational accuracy of existing infrastructure is by participating in a subsurface utility engineering (SUE) survey during the pre-construction phase of a project. A SUE survey typically involves both remote detection technologies such as EMI and GPR and confirmatory potholing which exposes underground utility and other infrastructure. Similarly to infrastructure exposed during construction, accurate locations can be determined by traditional survey techniques or methods such as that suggested by Costain and Bentley.

In some jurisdictions, there is legislation in place that mandates the improvement of locational accuracy of existing data. In The Netherlands, contractors are expected to report locational inaccuracies of the data that was provided to them upon verification by trial trench. Within reasonable time, the utility owner is then expected to improve the data to bring it up to the desired level of accuracy. In the regulations of the Leitungskataster (Utility Cadastre) of the City of Zürich in Switzerland, it is explicitly mentioned that data previously marked as inaccurate is to be updated once a suitable surveying opportunity (open trench) is available.

Successful programs to reduce damage to underground utilities

Over the years I have personally compiled information on 25 jurisdictions in the Americas, Europe, and Asia Pacific that have implemented policies and organizational structures for sharing information about the location of underground infrastructure (see Appendix for details about some of them). These include comprehensive programs involving many different stakeholders (Japan, Heathrow), government mandate (France, Japan, Calgary, Sarajevo, Bern, Jalisco MX, Sao Paulo BR, Netherlands, Estonia), single owner (Defence ministries and departments, universities, ports, hospital campuses, etc), government voluntary (U.S. Critical Information Protection Program, Singapore GeoSpace), NGO consortium (Integrated Cadastral Information Society, British Columbia), industry association/consortium (Common Ground Alliance, North America, Utility Strike Avoidance Group, UK, Pernambuco BR), government mandated, network operator or excavator financed (One call centres in North America, KLIP, Belgium, KLIC, Netherlands), Private one call (several states in U.S. and Australia, LinesearchbeforeUdig in UK), and regulatory with quality mandate (ANEEL Brazil electric power regulator). Two of these, Japan and Heathrow, have developed comprehensive programs that have successfully led to continued reduction in underground utility damage.

Japan

A number of cities, regions and countries around the world have recognized the importance of accurate information about the location of underground infrastructure and implemented processes to reduce the risk of these events. For example, comparing the United States and Japan reveals a startling difference in the number of incidents of underground utility damage during construction. The number of incidents in the U.S. is between 400,000 and 800,000 per year (roughly one or two every minute). For Japan available statistics suggest the number of incidents in 2016 was 134.

In order to better understand the remarkable success in Japan in avoiding damage to underground infrastructure, in 2003 GITA organized a study mission to Japan. Technical visits were made to individual ROADIC member organizations and a report was produced. This is an update to that report.

Background

The Road Administration Information Center (ROADIC) was originally created in 1986 as a result of several large-scale gas explosions that killed and injured hundreds of people and caused tremendous damage. These accidents were the result of a lack of knowledge about the location of underground infrastructure assets during excavation and construction activities. The Japanese national government saw the need to develop an approach to preserve public safety and to improve response to accidents involving this significantly expanding public energy source. The Ministry of Construction, Bureau of Roads, founded ROADIC as a non-profit consortium of public and private members including utility network operators (electric, gas, water, sewer, trains, subways and communications.) and prefectural road administrators to manage and protect utilities within the public right-of-way. Originally implemented in Tokyo in the mid-1980s, it has been extended to 12 major urban centres throughout Japan including Tokyo, Sapporo, Chiba, Kawasaki, Yokohama, Nagoya, Kyoto, Osaka, Kobe, Hiroshima, Kitakyushu and Fukuoka with a combined population of over 42 million.

The original cost of establishing the ROADIC program was about ¥ 9.5 billion,or US$ 87 million, sixty percent of which was funded by the national government and local governments. The remainder was contributed by interested-utility companies. The 2003 annual operating budget was ¥ 3.4 billion, or US$ 31 million. The national government and local government provide 60 % of the annual operating funds. The balance is divided among the individual regional member organizations. In 2019 the annual operating budget is ¥ 2.6 billion or US$ 24 million.

The Road Administration Information System (ROADIS), developed in the nineties under guidance of the Ministry of Land, Infrastructure and Transport (MLIT), went operational in 1998. ROADIS is a joint effort supported by road administrators and utility network operators that compile and manage the various information layers. The principle goal is to better plan and manage road maintenance and excavations by providing a central geographical information and data analyses centre. It's an online application containing combined information layers on road segments, topography, electricity, data communication, gas, water supply, sewage and metro with a map scale of 1:500. ROADIS is implemented by a custom-developed computer mapping software product developed by Tokyo Gas called TUMSY (for Total Utility Mapping System). TUMSY supports a number of functions in the areas of facility management, disaster management and emergency operations. Two separate information standards were developed to facilitate interoperable data communication.

ROADIC serves as the focal point for all road occupation permit requests. Prior to all excavations construction contractors are expected to contact utility network operators and to submit a pre-construction drawing. Since construction contractors do not have direct access to ROADIS, digital or paper maps extracted from ROADIS are provided to them by ROADIC members. According to the rules of Japanese road construction, painting or marking the road surface is not required.

ROADIS provides road administrators and utility network operators with data on each other's facilities in Tokyo and 11 other cities. Its data is used for road construction coordination and road occupation application / permission procedures. In addition to providing an efficient system for sharing this information among the road administrators and utility network operators, its broader social responsibility is preventing accidents during road excavation and preventing indirect effects of utility damage such as injuries and deaths, traffic congestion, lost custom and delayed and over budget construction. In addition to road construction, ROADIS data has also been used during emergencies such as earthquakes.

Outside of the areas covered by ROADIC, utility network operators rely on commercial GIS to provide maps showing the location of their facilities.

Statistical information about underground utility damage

There is not one central agency responsible for collecting information about incidents of underground utility damage. As part of a program to reduce accidents during construction the Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism maintains a record of construction accidents where occupational accidents and public damages are divided into two categories, damages to overhead utilities and other infrastructure and damages to underground infrastructure. For incidents involving a gas company, depending on the severity of the incident it may be required to send an accident report to METI (Ministry of Economy, Trade and Industry). Reporting to METI is mandatory for all incidents involving a high pressure gas transmission line and incidents involving deaths, injuries, supply problems, fires, explosions, and traffic disruption. There is no central historical record that compiles the number of incidents, injuries and fatalities, cost and other information by year.

In 2016 a survey was carried out to determine the amount of excavation damage resulting from excavation. That year there were 263,000 requests for location information about underground utilities. Of the 180 companies contacted 107 responded by reporting incidents of damage to utilities in that year. It was found that there were 134 incidents involving underground utility elements, like cables and pipelines, and 82 incidents for above ground structures. The available statistics suggest that the annual number of incidents has been declining since data was first collected in 1983.

Preventing damage to underground utilities during construction

In the event of damage to underground utilities resulting from excavation work, the construction contractor that caused the accident is generally held responsible for the response and repair costs.

Because ROADIS is a “closed” system, data and system access is limited to those organizations that are members. Contractors rely on digital maps provided by network operators and trial digging to determine the accurate location of underground infrastructure. Guidelines for construction are specified in the “Construction Public Disaster Prevention Measures Summary” from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). For all civil engineering work, network operators with facilities in the vicinity must be contacted in advance. Based on location information maintained by network operators, using the ROADIS system in major urban areas, the network operator will provide maps and determine how excavation should proceed including reinforcement, relocation, and backfilling. The network operator may also require the presence of a representative during construction. Before excavation can begin, the “*Construction Public Disaster Prevention Measures Summary*” stipulates that the location of utilities should be confirmed visually by trial digging. The *Occupation Entrepreneur Liaison Council* in which all utility network operators participate provides guidelines for excavation. The guidelines specify that all areas within 50 cm of underground utilities must be manually dug. Inaccuracies in the location of underground infrastructure exposed during construction by a contractor working for a specific network operator is reported to the network operator who updates the ROADIS system. There does not seem to be any guidelines requiring contractors who find inaccuracies in the location of other facilities to report them to the relevant network operator.

In the case of new infrastructure the as-builts submitted by the contracting company to the network operator are relied on for mapping underground utilities. It is not mandatory that newly installed facilities be surveyed by a licensed surveyor, but there is a standard for reporting the location of underground infrastructure which is based on the “*Rules for Work Regulations Based on Article 34 of the Surveying Law*” (last revised March 31, 2016). The accuracy of the as-built data is typically ± 10-20 cm. For gas infrastructure the covering and offset of underground lines reported by the contractor are in centimetres. The accuracy of the as-builts is confirmed by receiving the completed “cover book”. The cover book contains field measurement data such as the depth of the earth covering and offset measurement for the newly installed cables or pipes.

In Japan, all road construction must be approved by the relevant road administrators. The information collected during the application process including the location of any excavations is entered into ROADIS. After completion of construction, updated utility as-builts are provided to ROADIC. Using these drawings ROADIS utility maps are updated once a year. For the road data updating the roads data requires two years after completion of construction.

Other measures to reduce damage to underground utilities during construction

As part of a process of continuous improvement In 1990 ROADIC began to organize “study missions” to North American utilities, cities and other government agencies and private sector companies, European utilities and government organizations. These missions involved Japanese utility companies, government agencies and private sector service providers. This annual system of continuous improvement has contributed to the ROADIC system of Japan becoming a world-class example of multi-organizational cooperation and information sharing.

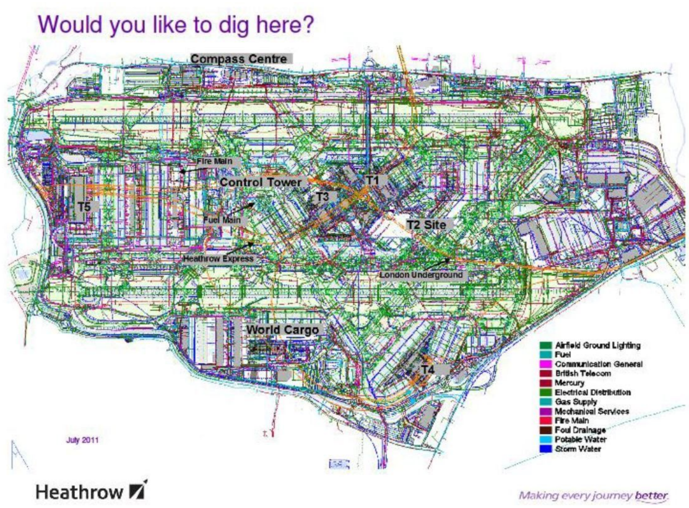
Other measures that have contributed to reducing damage to underground facilities include shared ducts and cable boxes for utilities. In addition, in urban areas road administrators organize coordination meetings which bring together representatives of road administrators and network operators to plan future road construction with the objective of shortening the construction period and ensuring safety.

Road administrators also regulate road construction to reduce the risk of damage. For example, in many jurisdictions regulations prohibit road excavation over a stretch of road for a certain period, typically about 5 years, after construction. This contributes to reducing the frequency of construction and the attendant risk of utility damage and traffic disruption.

Conclusion

Based on the available evidence it appears there are several reasons for the remarkably low number of incidents of underground utility damage in Japan. There is a high level of collaboration between road administrators and utility network operators. There has been a sustained effort to understand what other jurisdictions in North America and Europe are doing in this area. All road and utility network data is contained in a single repository for location information about underground infrastructure utility networks. (I am very surprised that the utility data is only updated once a year, but it may be that in Japan this data has low volatility compared to North America.) A construction culture that reliably generates as-builts with an accuracy of ± 10-20 cm. Regulations, business processes and a culture that motivates excavators to exercise extreme caution when digging near underground infrastructure. I suspect the risk of encountering unexploded ordnance from the second world war in major cities may further motivate excavators to exercise care during excavations.

Heathrow International Airport



Airports are like cities except that they have a greater density of underground utilities and more types of underground equipment; communications cables, aeronautical ground lighting cables, gas mains, low voltage electric power cables, high voltage electric power cables, storm water mains, sanitary waste water mains, potable water mains, grey water mains, fuel mains, fire fighting water mains, and a variety of underground structures with over 50 different owners. Heathrow's infrastructure includes more than 45 000 manholes, 72 miles of high pressure fire mains, power cables ranging from 9 V up to 400 KV, 81 miles of aviation fuel pipes ranging between 1.5 inches to 20 inches in diameter and between 3 and 115 bar in pressure. Furthermore striking an underground service in an airport carries with it a larger risk than in an urban area because of the incoming and outgoing aircraft and the large number of people in a concentrated area.

At Heathrow safety is the most important objective. It is essential for passenger, staff and contractor safety that everyone knows precisely where all of the underground infrastructure is. At Heathrow *Information Modelling* refers to a coordinated set of processes and information requirements that add value by creating, managing and sharing the properties of an asset throughout its life-cycle. The same principles apply whether it is a building, a gas main or an AGL light fitting on a runway. Information modelling provides a platform for asset management across the entire life-cycle - acquisition, commissioning, operation, maintenance and disposal - so that everyone involved works collaboratively sharing information in a common way. This makes it possible for the transitions from architect to designer to constructor to client within the acquisition phase to happen seamlessly.

A number of years ago Heathrow implemented a seven step process, from early design to handover, for excavations at Heathrow that continues to be followed today. One of the most important pieces of data that is maintained by Heathrow for underground assets are "*confidence codes*", which are a measure of how confident a surveyor is that he/she has pinpointed the utility service he/she located. There are a number of technologies for detecting underground facilities including electromagnetic, ground penetrating radar, acoustic, seismic and others, and they all require interpretation. Heathrow's confidence codes are a way of classifying the results of underground utility detection, verification and location undertaken by different survey methods:

- D – Desktop survey followed up with site reconnaissance.
- C – Use of underground scanning tools to locate services with a reasonable degree of confidence of what has been located.
- B – Detection - Use of two techniques to verify the location of the utility, for example, using Ground Penetrating Radar (GPR) to confirm the location found with an electromagnetic scanner.
- A –Verification - Digging a trial hole using a vacuum excavation/air pick or hand tools to expose the service, then surveying the location and extents to 25mm accuracy.

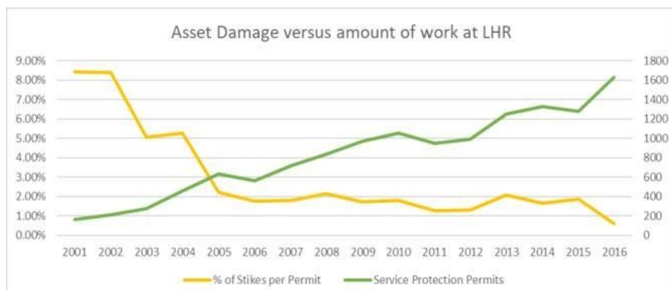
Heathrow has developed the concept of exclusion zones which uses these quality/confidence codes to restrict the type of excavation equipment can be safely used within 0 to 3 meters of a utility. These include hand-digging (foot pressure only), powered hand tools, vacuum or hydraulic extraction, and powered excavation.

Heathrow has developed a business process for continuous improvement of the location accuracy of underground infrastructure called the "*Validation Life Cycle*". It relies on a process that progressively updates confidence codes for underground facilities impacted by a construction project so that the information captured during a project is not lost but is integrated into Heathrow's asset database.

- Project manager sets scope and requests latest information

- Designer receives existing information
- Designer carries out site reconnaissance, applies confidence codes
- Designer/client/project manager agree on scope for survey
- Survey carried out increasing confidence codes
- Design completed, survey and design passed to constructor(contractor)
- Constructor surveys as they go increasing confidence codes
- Progressive handover to client for integration
- Information fully integrated into existing information

Heathrow Map Live is a web-based application that provides business visibility into model information. It is based on the Common Language (CL), which defines the structure of all asset information at Heathrow. Deliverables are progressive throughout projects. All information resides in two databases, Document Management and Asset Management System. These contain infrastructure and building models (BIM), design drawings, health & safety files, operation and maintenance manuals and asset maintenance information. This information provides the basis for operating the airport safely, and also helps management make informed decisions. In addition it helps Heathrow fulfil its legal obligations under the CDM (Construction Design Management) regulations and the Corporate Manslaughter Act.



As a result of these measures service strikes (accidentally hitting a utility cable or pipe) due to inaccurate information about underground infrastructure have declined at Heathrow by a factor of 6 since 2002 while total construction activity increased significantly.

Going forward Heathrow is planning to implement a "*Base Station*", an application which will be mandatory for all contractors. In the future Heathrow will only accept “as-built” information that is created using the Base Station application. Heathrow plans to review each company and user’s competence on a project by project basis.

Another key aspect of Heathrow’s program for reducing the risk of utility damage is training for skills development. Heathrow helped to develop National Vocational Qualifications (NVQs) relevant to underground asset management. National Vocational Qualifications (NVQs) are work based awards in England, Wales and Northern Ireland that are achieved through assessment and training. To achieve an NVQ, candidates must prove that they have the competence to carry out their job to the required standard. NVQs are based on National Occupational Standards that describe the 'competencies' expected in any given job.

Heathrow has supported the development of the PAS 128 standard for underground infrastructure. PAS 128 is aimed at the practitioner, surveyors who make their living detecting and reporting the location of underground utilities.

Heathrow has also supported the HSG47 guide *Avoiding danger from underground services* which is aimed at all those involved in commissioning, planning, managing and carrying out work on or near underground services. It outlines the potential dangers of working near underground services and gives advice on how to reduce any direct risks to people's health and safety, as well as the indirect risks arising through damage to services.

Recent innovative programs for managing location information about the underground

In the last few years several jurisdictions recognizing the importance of complete, accurate and uptodate location data about underground infrastructure have initiated innovative programs related to data about the underground.

Colorado mandates improved quality for underground utility location information

In 2017 there was an explosion at a home in Firestone, Colorado that resulted in two deaths and a serious injury. Previously in 2014 the Pipeline and Hazardous Materials Safety Administration (PHMSA) found that Colorado’s one call legislation did not assign an agency to enforce the legislation. In 2018 the Colorado legislature revised its one-call legislation. The latest legislation differs from the one call legislation in other states and provinces in two important respects:

- It explicitly mandates subsurface utility engineering (SUE) prior to engineering design for public civil engineering projects to determine the 2D location of underground utilities by a licensed professional engineer. This is intended to eliminate unnecessary and often expensive utility relocations.

- It has provisions to ensure the submission by network operators or their contractors of accurate “as-constructed” electronic drawings within 45 days after completion of construction. This is enforced by inspections with the possibility of civil penalties if the drawings are found to be non-compliant.

The real teeth in the new legislation for improving data quality by network operators is that it mandates CDOT to conduct quality control as part of construction oversight. Specifically, it requires third party inspectors registered with CDOT and paid for by the network operator to conduct construction oversight to ensure that the "as-constructed" PDFs submitted to CDOT accurately reflect what was actually installed in the ground. Various measures including denial of further construction permits and civil penalties can be levied against non-compliant network operators.

This is a ground-breaking initiative involving legislation, regulation and new technology to address one of the chief causes of highway construction delays and cost overruns.

Montana mandates survey grade as-builts for new underground infrastructure

Montana has recently revised its statutes governing the installation of utilities on state highway right-of-ways. The revised statutes mandate that as part of a new permitting process accurate electronic as-builts must be submitted to the Montana Department of Transportation (MDT) upon completion of construction. The new legislation has teeth. It requires that the as-builts must be signed by a licensed professional engineer (PE) or professional land surveyor (PLS). As-builts not signed by a PE or PLS are subject to inspection by the MDT to verify the accuracy of the as-builts at the utility owner's expense.

Colorado mandates open maps of underground oil and gas infrastructure

Colorado is also unique in that it has recently passed legislation to collect location information and publicly publish maps of underground gas flow and gathering lines. Senate Bill 181(2019) made the Colorado Oil and Gas Conservation Commission (COGCC) responsible for regulating previously unregulated gathering lines. New rules adopted by COGCC late in 2019 required the oil and gas industry to provide maps of their flowline and gathering system infrastructure. Much of this infrastructure had never before been documented or identified.

This rule making by COGCC has major implications for oil and gas companies. In 2013, Colorado had 58,200 miles of intrastate gas pipelines of which about 17,300 miles are gas gathering lines. As of November 2019 the COGCC had collected location information with an accuracy no less than ± 25 feet for about 7,000 miles of these lines. These maps are publicly available on the COGCC web portal.

Singapore plans to develop national map of the underground

Digital Underground

In 2017, the Singapore Land Authority, Singapore-ETH Centre, and the Geomatics Department of the City of Zürich started the Digital Underground project with an initial objective of developing a road map for achieving a reliable map of subsurface utilities. The DU project is looking at the whole workflow relating to underground infrastructure from data capture to application. This is a different approach from most of the rest of the world which takes a bury-and-find approach.

The objective of the first phase of the project was a set of recommendations for moving forward toward a reliable digital twin of Singapore's underground utilities. For existing utilities, advanced ground penetrating radar (GPR) technology was assessed to determine the effectiveness of GPR as a mapping technique with Singapore's soil conditions. An experiment was conducted which applied a combined LiDAR and ground penetrating radar array to capture above and below-scans of various areas in Singapore. Data modeling was a second key objective of the first part of the project. The goal was to develop a data model that enables the captured subsurface infrastructure data to meet the requirements of end users’ use cases.

The first part of the project generated a set of high level requirements to address the challenge of developing and maintaining an accurate map of underground utilities. The primary recommendation is to establish a single, consolidated national map of subsurface utilities that enables quality management and quality control all throughout the subsurface utility data life-cycle. Secondly a national mapping strategy for accurate mapping of subsurface utilities was proposed that is supported by two pillars. The first is to ensure that all newly built utilities are captured accurately. The second is to capitalize on data capture opportunities during the life-cycle of existing utilities. For example, capital construction projects are expected to benefit directly from utility mapping in the design phase, and the captured information can be consolidated for use beyond their scope and timeline. Other events, such as visibility or accessibility of utilities during trial trench, maintenance and rehabilitation works may provide suitable data capture opportunities that can each be matched with the appropriate data capture technique. Another key requirement is accessibility, that this data is available to the people that need it, i.e. land administrators, planners, designers, utilities and telecoms, construction contractors, and emergency responders, but in a way that protects privacy, does not reveal information about networks that could be used competitively, and prevents misuse.

Over the next two years, SLA and its partners intend to further develop the foundations of an ecosystem that supports and enables a reliable map of subsurface utilities. The project is intended to specify governance, legislation, capacity development, data capture standards, and a prototype platform for quality control and consolidation of 3D utility information for planning and land administration applications.

National standard for utility surveying

In August 2017 the Singapore Land Authority (SLA) released a standard and specifications for the procedure and practice of utility surveying in Singapore. It covers the surveying technologies (total station, RTK, or laser scanning) to be employed and the specific data elements to be captured. It also requires that location measurements be captured by a qualified professional (a

Registered Surveyor at the Land Surveyors Board of Singapore). Through the Singapore Government's regulatory authorities, this standard has progressively been mandated for all new utility construction projects.

The standard specifies the data that should be captured for new underground utilities including telecommunication, sewerage, water supply, electric power, gas, and drainage. It requires that after installing utilities and prior to filling the trenches an as-built survey should be performed by a registered surveyor to capture the location of the utilities to Quality Level 1. (The quality standard used in Singapore is; QL1) ±100mm horizontally and vertically, QL2) ±300mm, QL3) ±500mm, QL4) Unknown accuracy and QL5) Trenchless method.) In addition to location, the standard also defines the attribute information to be captured. For example, for an electric power cable, the standard specifies that x,y,z should be surveyed at 20 meter intervals for a straight line cable and more frequently for a curving cable. In addition, height, width, number of columns, number of rows, number of ducts, number of cables and quality level should also be captured. Together these data elements comprise a basic data model for sharing information about underground utilities.

UK plans to encourage sharing of location information about underground infrastructure

Among the first projects initiated by the recently formed Geospatial Commission was a process leading to the creation of a National Underground Assets Register (NUAR). The NUAR initiative was motivated by a perceived market failure to make available complete, accurate and current data covering the location of underground utilities and communications to those who need it for safe working. The objective of NUAR was to create a secure means to share information about underground infrastructure mainly among local government organizations, and utility and telecom network operators. The register is intended to show where electricity and telecom cables, and gas and water pipes are buried and is targeted on several use cases: safe digging to avoid utility strikes, on-site construction efficiency, site planning, data exchange, and improved coordination. The project started with £3.9 million allocated for two pilot projects split between Central London and the North East of England.

The system for sharing underground data for both pilots was provisioned by OS on an in-country cloud platform. It is built on an OGC standard data model and provides access to maps of underground utilities to handheld and other devices via a web-based user interface. A lot of the effort was devoted to security, privacy and protection of competitive information. For each network operator there is a terms and conditions document that defines the legal requirements for how that operator's data can be used, Queries are limited to 10,000 square meters for field user access and there are other limits to prevent multiple queries aimed at viewing an entire network. System users are network operators, local government, and contractors working for either of these.

One of the most important elements responsible for the success of the NUAR pilots in the North East of England and Central London was data protection. Data protection rested on three pillars; a legal framework, security technology, and trust. The legal framework comprised legal agreements with individual data providers governing how their data could be used. Security technology included encryption, two factor authentication, permissions-based access, limits to the size of the geographical area that could be queried (10,000 square meters for the most common user role), and a journaling system that keeps a record of all queries. Trust among the network operators and local government organs was essential to providing a cooperative environment where local utilities and telecoms were able to share their data and make it accessible to system users through an on-line hub.

The most recent implementation of the NUAR system was deployed in mid 2019 in the North East of England and as part of the pilot in Central London. There are two remarkable achievements of these pilots. The first is a secure legal framework within which municipal government organizations and network operators are able to safely and securely share their data. When a user accesses data of a network operator, there is a downloadable document associated with the data that defines the terms and conditions under which the data can be used.

The other remarkable element is that it makes it very easy to provide information about errors that are observed by stakeholders in the field, for example, if a contractor performing road work for a town council exposes pipes or cables that are not located where utility as-builts indicate they should be. The NUAR system enables a worker who notices an error in the field - a wrong location, incorrect type of equipment, or other problem - to enter corrected information about the location, type of equipment, and other information from a mobile device.

The NUAR project represents an important step forward in enabling the sharing of information about the location and other information about underground infrastructure that will contribute to reducing the risk of damage to underground utilities during construction. In April 2020 the project entered a preparatory phase paving the way for a regional MVP and national roll out.

Netherlands mandates sharing of underground geotechnical information

In 2015 the Netherlands embarked on a national program supported by legislation and standards to expand the collection and sharing of data about the subsurface. Legislation passed by the States General created the *Basisregistratie Ondergrond (BRO)* or *Key Registry for the Subsurface* which is open and accessible to all citizens of the Netherlands. The law mandated that if you excavate or drill you have to share your data with the BRO registry. In addition if when using the data in the registry you find something is incorrect it is mandatory to to report it.

The Key Registry for the Subsurface (BRO) came into force in January, 2018. On 26 June 2018, this data became publicly available via the Dutch open data portal PDOK. Work is underway to implement data models for all the 26 data types including geotechnics, soils, and groundwater that will become mandatory by 2022.

Recommendations

Based on the Japanese and Heathrow experience and a review of international initiatives to develop programs for underground infrastructure information (see Appendix), a set of recommended elements have been compiled that organizations and jurisdictions including national, state/provincial and municipal are using to address the challenge of damage to underground infrastructure. The Japanese and Heathrow experience have shown that to successfully reduce utility damage requires a comprehensive approach that implements most, but not necessarily all, of these recommendations.

1. **Reliable statistics are essential** to determine the social impact of underground utility damage and to assess the effectiveness of policies, procedures and technologies designed to reduce the number and severity of incidents of

underground utility damage. Every incident of damage to underground infrastructure should be reported including injuries, fatalities and direct cost. Cause is difficult to determine because it depends on who is reporting the incident. A network operator's perspective may be that the contractor did not exercise care during excavation, whereas the contractor's perspective may be that the location of the cable or pipe as identified as a result of a one-call request was inaccurate. In civil aviation each incident is investigated by the NTSB, an impartial group of experts who determine technical cause but do not assign blame. Indirect costs are nice to have, but typically difficult to estimate. Responsibility for submitting this information may be assigned to the network operator, the excavator, and/or to an independent organization. One option for efficient reporting is to classify incidents by seriousness and assign different levels of reporting based on this classification. For pipelines PHMSA assigns levels of seriousness based on cost, consequence, injuries and fatalities. The available evidence from the U.S. civil aviation industry, pipeline industry, and many national statistical agencies suggest incident reporting should be mandated to ensure statistically reliable data. This entails significant penalties for not reporting incidents. Ex. Pipeline and Hazardous Materials Safety Administration (PHMSA), Heathrow International Airport, Japan Construction Industry Association, Common Ground Alliance, Ontario Regional Common Ground Alliance, Colorado 811

2. **Subsurface utility survey (SUE) during planning and design.** Making the location of underground infrastructure available to engineers so that designers have access to not only accurate above-ground surveys but also accurate below-ground location information enables engineers to avoid underground infrastructure during design. In most jurisdictions in North America it is only required to contact the one call centre a few days before beginning excavation. Recent legislation In Colorado now makes it mandatory to conduct an SUE survey prior to engineering design. The entire area of the planned construction project must be assessed by a subsurface utility engineer (SUE) in collaboration with the utilities and telecoms with equipment in the area. In addition to known facilities shown on network operator as-builts, the SUE survey should include scanning with modern remote-detection tools (EMI, GPR and inertial and acoustic locating) to identify abandoned or unknown infrastructure. In Colorado the cost of the SUE survey is borne by the engineering firm. Furthermore, as the

Alabama DOT has found, to be maximally effective in avoiding unnecessary utility relocations the deliverable from the SUE survey should be a 3D model. Ex. Colorado 811, Alabama DoT, Cedar Falls

3. **More sustainable design.** Better design can improve the carbon footprint of underground utilities. For example, bends in pumped pipework due to clashes with unexpected external objects increase friction loss. Sharp bends can also inhibit the use of inertial location techniques. Bends in cables can cause increased resistance and heat. Also cables can be damaged when pulled through ducts with sharp bends.
4. **Make underground infrastructure easier to locate.** A number of technologies are available for this including using tracer wires, ball markers and other devices.
5. Applying **advanced technology for underground infrastructure detection**. Recent technical advances in GPR and new commercially available technologies such as acoustical and inertial locating and others provide increasingly accurate data about the location of underground utilities and reduce the need for expensive potholing and safe digging techniques such as vacuum and hydraulic digging. Ex. GPR, EMI, acoustic and inertial locating
6. **Enhanced survey procedures for locating unknown and abandoned facilities.** The current one-call system is targeted toward utilities locating their own facilities, typically based on their as-builts. But there is no formal mechanism for locating facilities that have been abandoned or are not shown on network operator as-builts. Requiring a full SUE survey in addition to a traditional surface survey as part of planning and design at the beginning of a construction project helps avoid surprises during construction that can delay projects. In the Netherlands there is an approach enshrined in legislation whereby local government "adopts" underground objects that have not been claimed within a defined time period. Ex. SUE survey required by Colorado 811
7. **Capturing location information for infrastructure detected as the result of an information request to one call**. Currently when notified by a one call centre in response to a request for underground utility information, utilities are required to mark the ground in the area of the proposed excavation. In some jurisdictions network operators are also required to provide a paper sketch showing the location of underground utilities. Excavators often validate this information by potholing. To avoid locating the same facilities over and over again, this information needs to be

digitally captured and shared with the objective over time of building up a high quality (QL A and B) shared database of the location of underground infrastructure. Ex. Colorado 811, Public Works Canada

8. **Capturing accurate location information for infrastructure exposed during construction.** In the United States it is estimated that $10 billion is spent annually to locate underground infrastructure prior to and during construction. Much of this information is not shared and the next time excavation occurs in the same area, the underground infrastructure must be located again. If this information is captured and shared, over time a high quality (QL A and B) database of the location of underground infrastructure can be achieved that avoids locating the same infrastructure over and over again. Technical alternatives for recording the location of exposed infrastructure include total station, RTK, and laser scanning. It is essential that this does not increase costs for the excavator. Contractor margins are tight and keeping a survey crew on hand during excavation significantly increases costs. There have been experiments Costain and Bentley aimed at efficiently capturing the location of utilities exposed during construction using handheld devices and consumer cameras mounted on excavation equipment. In Colorado the Pointman handheld application enables efficient capture of utility relocation information from the field during construction. Ex. Japan, Colorado 811
9. **Efficient processes for updating location information recorded in network operators' databases from the field.** Information captured as part of a SUE survey, as a result of an information request to one-call/811, or detected during excavation may differ from the records contained in network operators' databases. For continuous improvement of the quality of the information about the location of network facilities requires an efficient way to compare and update this information. The NUAR online system supports “observations”, which allows anomalies to be tagged from a handheld device in the field. In Colorado the Pointman handheld application enables efficient capture of utility relocation information from the field during construction.Ex. NUAR, Colorado 811
10. **Legislation, regulations and construction practices that generate complete and accurate as-constructed drawings for new underground infrastructure.** If the location of all new underground utilities including replacements is captured to cm accuracy, the accuracy of utility and telecom GIS data will gradually improve.

Alternatives for recording the location of newly installed infrastructure include total station, RTK, LiDAR, and smartphone photogrammetry with accurately known control points or reference structures. Whatever the technology the result should be cm accuracy. Special provision must be made for capturing the location of facilities installed using horizontal (trenchless) drilling, for example, inertial mapping for pipe networks. Since reliable as-builts are generally a network operator responsibility - policies are required to ensure that as-builts for newly installed equipment are accurate. There are several ways to do this; legislation which enables a government or regulator to conduct QA/QC checks on submitted as-builts or a shared liability model that assigns responsibility for subsurface utility damage to network operators whose as-builts are inaccurate or out-of-date. Ex. Colorado 811, Calgary, Singapore, Bern

11. **Reducing or eliminating the as-built backlog.** If the time it takes for as-built information to enter the utility GIS or other database from the time new infrastructure is installed is measured in months or longer, the utility GIS is not sufficiently reliable for locating underground infrastructure for construction purposes. The objective should be better than a day. This can be resolved by regulation or by a suitable liability model. Ex. Ofgem in the U.K. requires as-built backlogs to be less than 42 calendar days. Colorado DoT requires submission of electronic "as-constructed" drawings within 45 days of completion of construction. Ex. Colorado 811, NUAR
12. **Reducing or eliminating the update backlog.** Utilities regularly maintain underground infrastructure, move it as part of a construction project, or abandon it. This information has to be reported back to the network operator to update the information in the utility GIS. There are two dimensions to updates; the accuracy of the location information provided from the field and the update backlog, the time it takes for updates to be entered in the utility GIS. As with the as-built backlog this backlog can stretch into months. The objective should be better than a day. This issue can also be resolved by regulation or by a suitable liability model. Ex. Ofgem in the U.K. requires backlogs to not exceed 42 calendar days. Ex. NUAR
13. **Standard for quality/confidence levels for location of underground infrastructure.** Quality standards such as PAS 128 in the U.K., ASCE 38-02 and 38-20 in the U.S., CSA S250 in Canada, and DICT in France provide information about the confidence level of the 3D location of underground assets. In some

jurisdictions the assigned levels may be used to determine the appropriate type of excavation equipment. They may also provide the basis for a shared liability model. Ex. Colorado 811, Heathrow International Airport, Japan, Singapore, France DICT

14. **Digitalizing the capture and sharing of information about the underground.** In North America, most one-call legislation only requires marking the ground prior to the initiation of construction. In Colorado and Ontario a written sketch is required in addition to marking the ground. British Columbia is the only jurisdiction I know of in North America that offers the alternative of the exchange of only a written record of the location of utilities mapped prior to excavation - no visit to the site to mark the ground is required. This is much more efficient for one call because it obviates the need to visit the site of the proposed excavation. In Colorado the Colorado Oil and Gas Conservation Commission (COGCC) has recently been made responsible for regulating previously unregulated natural gas gathering lines. As of November 2019 the COGCC had collected information on about 7,000 miles of flow lines and published maps of these flow lines on their website, which is open to the public, with an accuracy of no less than plus or minus 25 feet. Ex. ROADIS (Japan), KLIP (Flanders), KLIC (Netherlands), British Columbia one call, and Colorado COGCC
15. **A generally recognized standard for sharing information about the subsurface.** The Open Geospatial Consortium (OGC) is developing an underground information exchange standard, MUDDI, that is intended to provide an open standards-based way to share information about the below ground. There are a number of data models for different types of underground infrastructure and geotechnics. MUDDI builds on and augments existing standards to create a unified model supporting multiple use cases. The MUDDI model is intended to support routine street excavations, emergency response, utility maintenance programs, large scale construction projects, disaster planning and response, and smart cities programs. For street excavations the requirement is location of all entities with high horizontal, medium vertical accuracy (2.5D) of underground infrastructure; for large construction projects, detailed 3D geometry of underground infrastructure and detailed 3D geotechnics; for emergency response, interdependencies between different networks; for utility maintenance, network topology and facility location and condition; and for smart cities the ability to monitor and relate streams of data from sensors. This has not yet been adopted by a jurisdiction, but the Ordnance Survey, Singapore

Land Authority, and Fund for the City of New York) are actively supporting the development of the OGC standard. Ex. MUDDI (OGC)

16. **Mobile access to maps showing underground asset location and other information.** Underground utility location data should be available to all construction stakeholders via handheld devices for viewing and for updating during construction. Ex. Colorado 811, Colorado COGCC, NUAR
17. **All underground asset location information including utilities, telecom, and unknown and abandoned equipment combined in a single map.** This can be achieved either through ETL processes with a single physical database or a federated database composed of multiple physical databases. Each utility and telecom retains custodial control over its own network data. In some jurisdictions local governments are assigned responsibility for unknown and abandoned facilities. Ex. Colorado 811, Japan, Calgary, NUAR
18. **Improvement in the quality of network operators' underground facilities location information.** In North America the advantage of the current one-call system is that it requires that underground facilities be mapped to ASCE QL B before starting construction. Locating crews from network operators are required to visit the site of a proposed excavation just prior to construction to scan the ground for their facilities using EMI and GPR and mark the location of their facilities. If network operators' data were more complete, accurate, and current, a more efficient system would be fully digital like KLIC and KLIP. The latest Colorado 811 legislation requires that network operators provide accurate as-constructed drawings and provides for inspections to verify the reliability of the submitted construction drawings. A similar process with inspections by the City is incorporated in a by-law of the City of Calgary. Shared liabilities such as are mandated in France provide incentives for network operators to improve the quality of their location information. Another way that has been used to incentivize accurate as-builts is to tie payment to contractors to the submission and verification by the network operator of as-builts. In Bern, Switzerland implementation of an online system for sharing information about the location of underground utility location information, was followed by significant investment by Swisscom and utility network operators to improve the quality of their information. For new utility installations Singapore requires a survey by a certified surveyor to ensure accurate recording of location. Such an approach is expected over time to

result in improved reliability of location data. Ex. Singapore, Bern, Colorado 811

19. **Rules for the appropriate type of excavation equipment** based on quality level. Rules are required that restrict the type of excavation equipment based on the quality level of underground utilities identified by network operators. For example if facilities have been assigned ASCE quality level C or D, only hydraulic, vacuum or hand excavation may be used. Ex. Heathrow International Airport, Japan
20. **Data protection.** To enable this information to be useful in reducing the risk of underground infrastructure damage during construction it has to be shared in a secure way which respects privacy. In particular it must protect competitive information. One of the most important elements responsible for the success of the NUAR pilots in the North East of England and Central London was data protection. Data protection rested on three pillars; a legal framework, security technology, and trust. The legal framework comprised legal agreements with individual data providers governing how their data could be used. These agreements are available on-line to all users of the NUAR system. Security technology included encryption, two factor authentication, white listing, soft horizons, limits to the size of the geographical area that could be queried (10,000 square meters), and a journaling system that allows all queries to be reviewed to look for patterns of potential abuse. Trust among the network operators and local government organs in the North East was essential to providing a cooperative environment where all major local utilities and telecoms in Newcastle were comfortable with sharing their data and making it accessible to system users through an on-line hub. Ex. Colorado 811, KLIP, KLIC, NUAR
21. **Shared liability model** for costs of underground utility damage. The advantage of a rule-based shared liability model that assigns varying levels of responsibility to both contractors and network operators is that it provides motivation to network operators to improve the quality of their location information about their underground infrastructure, existing and new. An example of a shared model is the following: if a network operator identifies the location of a piece of underground equipment as Quality Level A according to the ASCE 38-2 standard and an excavator hits it, the excavator would be liable for costs if the facility was where the network operator said it was, or the network operator would be \liable if it wasn't. For an excavator intending to dig in an area where there is underground infrastructure assigned to

level C or D, the cost to bring all infrastructure to quality level B would lie with the network operator (as it does now with North American one-call systems). If the network operator declines to do this, the liability for any underground damage would lie with the network operator. Ex. France DICT

22. **Business processes for continuous improvement** in the location reliability of underground infrastructure. Similar FAA objectives in the civil airline industry, some jurisdictions have implemented a program for continuous improvement in the infrastructure. completeness, accuracy and currency of location information about underground utility Ex. Heathrow, Japan, Colorado 811
23. **Training in underground infrastructure detection and surveying** for practitioners. Ensuring that those involved in the detection, locating, and mapping of underground infrastructure are trained in the appropriate technologies and techniques to ensure completeness, accuracy and currency in the data they collect and manage. For example, Heathrow helped to develop National Vocational Qualifications (NVQs) relevant to underground asset management. National Vocational Qualifications (NVQs) are work based awards in England, Wales and Northern Ireland that are achieved through assessment and training. The Colorado Prostar system requires users to be familiar with both GIS and survey techniques. Ex. Japan, Heathrow, Colorado 811
24. **High degree of collaboration** between all stakeholders including network operators, consulting engineers, contractors and project owners. This has similarities with a BIM approach to construction and like BIM it is fostered by a shared 3D model Ex. Japan, Heathrow, Colorado 811
25. **A viable business model** to maintain adequate funding for the program. For example, one call/811 centres in North America are legislated at the state/provincial level, but funded by network operators and at no cost to excavators. Locates in response to notifications by one call centres are entirely funded by network operators at no cost to excavators. In contrast in the Netherlands a significant source of funding is the fee that excavators must pay for each information request. One of the open questions in the early stages of the NUAR project is how the operation of the register is going to be funded. It could be funded by local government and network operators, it could be partially funded by excavators along the lines of KLIC in the

Netherlands or as a subscription model where asset owners pay, such as LSBUD or Vault. Alternatively, it could be funded by a level of services model in which some services that might only be used by large organizations would require payment while other services could be free, and there are other alternatives.

A successful program for reducing underground utility damage requires the involvement of many stakeholders including network owners and operators, planners, surveyors, SUE engineers, design engineers, construction contractors, regulators and government agencies such as MOTs/DOTs need to be involved. The goal is to reduce the risk of utility damage over the life-cycle of infrastructure from planning through operations and maintenance. A successful program not only reduces underground utility damage and the associated costs, injuries and fatalities and results in more projects on-time and on-budget, but also significantly reduces the cost of infrastructure construction and maintenance. Additionally there are significant benefits for the construction industry. For example, reducing risk reduces insurance costs for an industry where margins are very low. Furthermore, developing and maintaining an accurate 3D map of underground infrastructure has potential benefits for other use cases beyond construction such as utility outage management, disaster planning, emergency response, urban digital twins and smart cities.

Appendix International initiatives relating to underground infrastructure

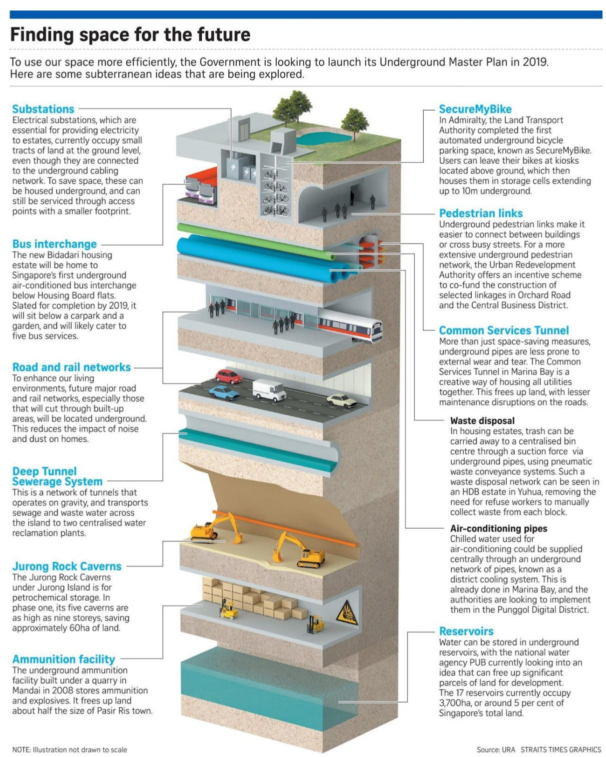
Over the years I have personally compiled information on 25 jurisdictions in the Americas, Europe, and Asia Pacific that have implemented policies and organizational structures for sharing information about the location of underground infrastructure. In this appendix details are provided for some of them..

Nationally mandated map of the underground

Singapore

Digital Underground project

A number of years ago 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. The Urban Redevelopment Authority's (URA) Draft Master Plan 2019, which guides Singapore's development for the next 10 to 15 years, identified increased use of underground space as one of its strategies to create more space for Singapore's growing needs.



Singapore has recognized that insufficient quality of information about the subsurface can lead to poor decisions, unnecessarily lengthy planning processes, increased cost of construction, more litigation and missed business opportunities.

When designing and building new utilities and other facilities underground, a reliable map is needed to plan for the optimal use of scarce and often already congested space and avoid utility damage causing loss of service and creating delays in the construction process. Land ownership regulations require an accurate record of the alignment of subsurface utilities in order to minimize conflicts in the use of underground space.

Although professionals from land development agencies, utility owners, and engineers in Singapore are able to access various sources of utility information, this information cannot be considered reliable. It lacks accuracy, does not always represent the latest and current situation, and may not be complete, lacking information on legacy utilities. Furthermore, data quality itself is a largely unmanaged and unknown aspect, leading to uncertainty. Recently in Singapore, important steps have been taken to ensure that all newly built utilities are captured according to the same standard and exclusively by qualified persons. However, the lack of quality of existing information remains to be reconciled. Similar to the U.S. and the UK, in Singapore the contractor has full liability for damage to underground infrastructure, which means there is little motivation from the perspective of liabilities for network operators to improve the quality of their location information about underground utilities.

In 2017, the Singapore Land Authority, Singapore-ETH Centre, and the Geomatics Department of the City of Zürich started the Digital Underground project with an initial objective of developing a road map for achieving a reliable map of subsurface utilities. The DU project is looking at the whole workflow relating to underground infrastructure from data capture to application which is a different approach from most of the rest of the world which takes a bury-and-find it approach.

One of the first activities of the Digital Underground project was to assess the state of the art for reality data capture technologies and how these might be used to improve the accuracy of underground data for both new and existing buried utilities. The first phase of the project resulted in a set of recommendations for moving forward toward a reliable digital twin of Singapore's underground utilities. These represent a comprehensive checklist of how a national government can begin to address the pressing problem of creating a reliable digital twin of underground utilities.

For new infrastructure, non-conventional reality capture techniques were documented. For open trench utilities, this included the use of handheld laser scanners. For trenchless construction, a technique for determining location by pulling a gyroscopic mapping device through pipes was investigated.

For existing utilities the latest ground penetrating radar (GPR) technology was assessed to determine the effectiveness of GPR as a mapping technique with Singapore's soil conditions. An experiment was conducted which applied a combined LiDAR and ground penetrating radar array to capture above and below-scans of various areas in Singapore. The experiment contributed to an assessment of the quality of Singapore's underground infrastructure information and the feasibility of large area utility mapping techniques. Singapore soils are not particularly good for GPR, which is able to penetrate down to 2 meters. The DU project collaborated with Leica Geosystems and IDS GeoRadar to deploy the Pegasus:Stream, a combined LiDAR and ground penetrating radar array, for the first time in Southeast Asia. It was used to capture above and below-scans of nine distinct areas in Singapore. In the Toa Payoh estate, which has undergone continuous development since the 1960s, data was captured along a 1.8 kilometre four-lane road at a speed of 15 kilometres per hour. Scanning of the entire area took five hours. Post-processing of the data back in the office required three weeks. A total of 109 subsurface pipes and ducts were detected in the area. By comparing the detected utilities to available information on existing utilities, it was found that in older areas the location of a lot of underground infrastructure was not recorded or does not have an accurate location. Only around 30% of detected utilities could be identified using the existing information. For newer areas, this figure was higher, but many detected utilities linking to new developments were not mapped yet.

Data modeling was a second key objective of the first part of the project. The goal was to develop a data model that enables the captured subsurface infrastructure data to meet the requirements of end users' use cases. With the data collected with LiDAR and GPR, the Digital Underground team explored how available map data and the subsurface utilities detected during the pilot could be combined to create a 3D model that could be fused with Singapore's cadastral maps. The results were showcased in a demonstrator application highlighting the value of reliable 3d information subsurface utilities for land administration purposes.

The first part of the project resulted in a set of recommendations for moving forward toward a reliable digital twin of Singapore's underground utilities. These provide a set of high level requirements at a national level to address the problem of accurately mapping underground utilities.

The first recommendation is to establish a single, consolidated national map of subsurface utilities that enables data quality management. Secondly a national mapping strategy for accurate mapping of subsurface utilities is proposed that is supported by two key objectives. The first is to ensure that all newly built utilities are captured accurately (survey quality). The second is to capitalize on data capture opportunities during the operate and maintain phase of existing utilities. For example, capital construction projects are expected to benefit directly from utility mapping in the design phase, and the captured information can be consolidated for use beyond their scope and timeline. Other events, such as visibility or accessibility of utilities during trial trench, maintenance and rehabilitation works may provide suitable data capture opportunities that can each be matched with the appropriate data capture technique. Another key requirement is accessibility, that this data is available to the people that need it, i.e. land administrators, planners, designers, utilities and telecoms, construction contractors, and emergency responders, but in a way that protects privacy, does not reveal information about networks that could be used competitively, and prevents misuse.

After the completion of the first part of the Digital Underground project, over the next two years, SLA and its partners intend to further develop the foundations of an ecosystem that supports and enables a reliable map of subsurface utilities. The project will cover a wide array of themes such as governance, legislation, capacity development, data capture standards, and a prototype platform for quality control and consolidation of 3D utility information for planning and land administration applications. One of its early results is the launch of Digital Underground Connect: a community of practice for subsurface utility mapping together with Bentley Digital Advancement Academies.

Standard for utility surveying

In August 2017 the Singapore Land Authority (SLA) released a standard and specifications for the procedure and practice of utility surveying in Singapore. The *Standard and Specifications for Utility Survey* in Singapore has progressively been included in contractual agreements for all newly built utilities by utility regulatory authorities. The standard is for open trench cases only. It covers the surveying technologies to be employed, the data to be captured, and specifies that a qualified professional (a Registered Surveyor at the Land Surveyors Board of Singapore) is required.

The standard specifies the data that should be captured for new underground utilities including telecommunication, sewerage, water supply, electric power, gas, and drainage. It specifies that after installing utilities and prior to filling the trenches an as-built survey should be performed by a registered surveyor to capture the location of the utilities with horizontal accuracy of ±100mm and vertical accuracy of ±100mm. It specifies that the survey equipment to be used should be a total station, GNSS Real Time Kinematic (RTK), or 3D Laser Scanning.

This standard is not mandated by the Singapore Government but is intended to provide a baseline to be incorporated in construction contracts. Since 85% of land is owned by the Singapore government, if a major government agency such as the Urban Redevelopment Authority (URA) routinely incorporated this standard in its contracts as part of standard procurement practice, it would effectively become a *de facto* mandate.

In addition to location, the standard also defines the attribute information to be captured. For example, for an electric power cable, the standard specifies that x,y,z should be surveyed at 20 meter intervals for a straight line cable and more frequently for a curving cable. In addition, height, width, number of columns, number of rows, number of ducts, number of cables and quality level should also be captured. The quality standard used in Singapore is; 1) ±100mm, 2)

±300mm, 3) ±500mm, 4) Unknown accuracy and 5) Trenchless method. In Singapore most underground utility work is open trench, although there is some trenchless for which the standard requires gyro surveying.

The standard does not specify format or what is to be done with the as-built information. Currently in Singapore there is nothing in place to require sharing of information about the underground like Netherland's BRO or the UK's National Underground Asset Registry (NUAR) project. But there is a Digital Underground project underway to create an ecosystem for a digital twin of the underground as part of the Mapping Singapore in 3D project. The Digital Underground project was initiated by the Singapore Land Authority with the support of the Urban Redevelopment Authority. The standard for underground utility surveying would create a basic data model for sharing information about underground utilities.

Nationally mandated information sharing about the underground

UK background

It is estimated that about 50% of the time overruns on commercial building projects are caused by unforeseen ground conditions. There are two aspects to the problems associated with the subsurface. One is geotechnics, soil, ground water, and geology conditions. The other is the location of underground infrastructure, utilities, telecommunications and other cables and pipes. There are growing government, private sector and standards initiatives in both of these areas in the U.K. to improve the information and sharing of information about the subsurface.

Public safety is an important social driver for improving knowledge about the underground. I remember attending a Pipeline Industries Guild (PIG) conference in Birmingham, U.K. in 2005 where the focus of the entire event was to motivate the pipeline operators industry in England to voluntarily participate in a call-before-you-dig centre that would reduce the risk of damage to underground infrastructure during excavation. There had been a near major disaster in Birmingham (Hunton Hill) when a gas company crew had attempted what was supposed to be a routine tap into a gas main to connect a new customer. Three drill bits later, the crew knocked off. Fortunately an ESSO contractor just happened to pass by and recognized that the gas crew had been attempting to tap into a high pressure fuel line. At the conference the section of pipe with dimples caused by the gas crew was shown. A number of experts described the extent of the disaster that would have followed if the crew had tapped into the line.

One of the problems is that every construction project involves considerable effort to discover subsurface geotechnical conditions and the location of underground infrastructure in the area to be excavated, but normally the data generated by this discovery effort is used for one project and not shared. For geotechnical information the Dig to Share project, supported by Atkins, British Geological Survey (BGS) and Morgan Sindall, is addressing this problem. Its aim is to develop a fully digital workflow, which is accessible to the whole industry, to upload and access data from the BGS web-based system. This will be developed on top of the existing system hosted and maintained by BGS.

The Vault system adopted in Scotland securely delivers integrated information on utility and other underground apparatus to over 300 unique users across 47 different organizations, with an average of 30 unique users daily. Recent legislation in Scotland paves the way for mandatory participation in Vault. The LinesearchbeforeUdig (LSBUD) offers something similar to a North American one-call centre. It offers a voluntary free to use service which anyone planning excavation can use to check for underground utility assets that LSBUD's 75 members (network operators) have in the area of the planned excavation. LSBUD is supported by its members which include all fuel transmission companies, 60-70% of electric power network operators, and some water and telecom operators in England. digdat (Anglian Water Services) is another one call system in England which is primarily focussed on underground assets of water utilities and telecoms.

But the UK has not had access to comprehensive statistics on all underground utility strikes similar to the Common Ground Alliance in North America. Since 2013 the Utility Strike Avoidance Group (USAG) has begun collecting statistics on underground utility damage. USAG operates on a voluntary basis with no direct funding other than the support offered by member organizations.

One area that would directly benefit from shared location information about the subsurface is street works. In 2004 the UK Parliament passed the Traffic Management Act, which gave highway authorities greater power to manage traffic disruption caused by 2.5 million roadworks that take place in England each year. In particular it requires excavators to apply for a permit (as Bern has done) for road work providing information about the location and timing of the proposed road work. Late last year the Department for Transport announced an investment of

£10 million in Street Manager, a digital planning service that will generate real time data about street construction. It will be free for technology companies and app developers to use. This will allow services like Waze (whose vision is to eliminate traffic congestion) and startups to build apps that help motorists avoid congestion caused by road construction.

The Traffic Management Act also enables local councils to charge a fee for permitting road work. One way of using this power is referred to as lane rental. Pilots have been carried out in several locations in England and have been found to reduce congestion by half on busy roads. For this to be used effectively requires accurate locate information about underground utilities and communications infrastructure.

A process to update the 2014 Publicly Available Specification (PAS) 128, has just been initiated. PAS 128, developed under the auspices of the British Standards Institution (BSI) and sponsored by the Institution of Civil Engineers (ICE) and others, is one of the few that reflects the advances in underground detection technology - hardware and software - that have occurred in the last few years. That it is now being updated suggests that PAS128 will continue to stay current with the underground detection technology curve.

The Open Geospatial Consortium MUDDI initiative to develop a standard for sharing information about the subsurface, including both geotechnics and underground infrastructure, is supported by the Ordnance Survey and supports several U.K. and INSPIRE standards.

Another important initiative in the UK is Project Iceberg which is focussed on the enabling of a single digital twin linking above- and below-ground infrastructure. Combining above- and below-ground information into one national single data model/data exchange framework will allow industry to share business developments and innovation activities. Project Iceberg is an exploratory project undertaken by the British Geological Survey, Ordnance Survey and the Future Cities Catapult to investigate ways to integrate data and services relating to the underground with other city data. To date two reports *Market Research into the Current State of Play* and Global Case Studies and Defining the Problem Space for an Integrated Data Operating System Above and Below Ground have been published.The medium term objective is to take these concepts forward with project partners to develop new digital data demonstrator projects.

Together these government, private sector and standards initiatives reflect the accelerating recognition in the UK of the importance of sharing information about subsurface geotechnics and infrastructure for public safety and construction productivity.

National Underground Asset Register (NUAR)

In the 2017 autumn budget the Chancellor of the Exchequer announced an important initiative to increase the value of the contribution of spatial data to the UK economy. The Geospatial Commission was created in the centre of government, as an independent, expert committee. It aims to unlock the significant economic opportunities offered by geospatial data and to reinforce the UK's geospatial expertise on the global stage.

To provide strategic oversight of the geospatial landscape in the UK, the Commission provided a £5 million fund to support collaborative data projects across 6 Partner Bodies - Ordnance Survey, HM Land Registry, British Geological Survey, Valuation Office Agency, UK Hydrographic Office and Coal Authority who between them hold most of the governments high quality geospatial data.

Among the first projects initiated by the Geospatial Commission was a process leading to the creation of a National Underground Assets Register (NUAR). The NUAR initiative was motivated by a perceived market failure to create and maintain complete, accurate and current data covering the location of underground utilities and communications.

The objective of the NUAR project was to create a secure means to share information about underground infrastructure among local government organizations and utility and communications network operators. The register is intended to show where electricity and telecom cables, and gas and water pipes are buried and is targeted on several use cases: safe digging to avoid utility strikes, on-site construction efficiency, site planning, data exchange, and improved coordination. The project started with £3.9 million allocated for two pilot projects split between Central London and North East of England.

The system for sharing underground data for both pilots was provisioned by OS on an in-country cloud platform. It is built on an OGC standard data model and supports OGC standards such as WFS for data exchange which enables most GIS products such as QGIS and ArcGIS to access it. A lot of the effort was devoted to security, privacy and protection of competitive information. For each network operator there is a terms and conditions document that defines the legal requirements for how that operator's data can be used, Queries are limited to 10,000 square meters for field user access and there are other limits to prevent multiple queries aimed at viewing an entire network. System users are network operators, local government, and contractors working for either of these.

One of the most important elements responsible for the success of the NUAR pilots in the North East of England and Central London was data protection. Data protection rested on three pillars; a legal framework, security technology, and trust.

The legal framework comprised legal agreements with individual data providers governing how their data could be used. As part of the legal agreement the terms on conditions for the platform and each data provider are available on-line to all users of the NUAR system.

Security technology included encryption, two factor authentication, permissions-based access, limits to the size of the geographical area that could be queried (10,000 square meters for the most common user role), and a journaling system that keeps a record of all queries.

Trust among the network operators and local government organs was essential to providing a cooperative environment where all major local utilities and telecoms were able to share their data and make it accessible to system users through an on-line hub. System users including network operators, local government organs, and contractors working for either of these. Trust was fostered by Ordnance Survey (OS), the developer of the software system, which has a long history in the U.K. as a trusted data broker.

Using an earlier prototype version of this platform in 2018 OS and Northumbrian Water undertook to create a map of underground infrastructure in Newcastle on Tyne. The objective was to compile in collaboration with utilities, local authorities and partners a combined infrastructure map for small sample areas including water, wastewater, gas, electricity, telecoms and other underground services. The project benefited from a spirit of cooperation - all major local utilities and telecoms in Newcastle were happy to share their data and had vector data available to contribute. The result was a database where each utility was steward of its own data which was shared through a hub. Interoperability based on OGC standards was demonstrated with three different GIS systems consuming the combined underground data through APIs. The data could be ingested into GIS systems with internet access, regardless of format and provisioned to both field engineers and planners.   As part of this experiment in creating a shared map of underground utilities, contractors were brought in to actually dig a hole so that participants could experience first hand what is involved in excavating to determine the location of buried utility assets. OS created a web interface to enable excavation teams in the field to access the data relevant to them via a mobile device. By the end of the week it was possible to demonstrate a working system that allowed excavators to query the map of underground utilities and use this information during excavation and construction. At the innovation festival a data sharing agreement was developed that all parties agreed to – Northumbrian Water, Northern Gas Networks, Northern Power Grid, Openreach, Durham County Council, Newcastle and Sunderland City Councils, Cranfield Soil and Agrifood Institute, British Geological Survey and Ordnance Survey.

Following the innovation festival the participants formed the *North East Underground Infrastructure Hub* (NEUIHub) consortium in order to progress the creation of a 'Common Infrastructure Map' implementing a dataset that contains almost full water, gas, electricity and a great deal of telco data for the city of Sunderland.

The most recent implementation of the NUAR system was deployed in late 2019 in the North East of England and as part of the pilot in Central London. When I was in Newcastle for a meeting of the NUAR Advisory Group, we went out in the field with an iPad to compare the network information available on the NUAR pilot system with above-ground visible infrastructure, manhole and handhole covers with distinctive designs allowing the below-ground network to be identified. While the quality of the data was what I expected from utility as-builts (PAS 128 quality level D), the remarkable part of the experience was being able to see all the underground networks, water, wastewater, electric power, gas, and telecom, in the query area together on the screen - a very rare experience anywhere in the world.

The Central London pilot is covering the area of six boroughs in Central London. While the vast majority of relevant data has already been vectorized in the Northeast of England, this is not necessarily the case in London.The Greater London Authority (GLA) will provide funding to local authorities to locate data and upgrade its format for use within the pilot platform. To enable comparison of vector and raster data, for three of the boroughs all the data will be vectorized. For the remainder various formats including raster will be used.

There are two remarkable achievements of these pilots. The first is a secure legal framework within which municipal government organizations and network operators are able to safely and securely share their data. When a user accesses data of a network operator, there is a downloadable document associated with the data that defines the terms and conditions under which the data can be used.

The other remarkable element is that it makes it very easy to provide information about errors that are observed by stakeholders in the field, for example, if a contractor performing road work for a town council exposes pipes or cables that are not located where utility as-builts indicate they should be. In the NUAR pilot system these are called *observations* and are represented by green triangles associated with the incorrectly located features. Observations enable a worker who notices an error in the field - a wrong location, incorrect type of equipment, or other problem - to enter corrected information about the location, type of equipment, and other information from a mobile device.

One of the open questions at this early stage of the NUAR project is how the operation of the register is going to be funded. It could be funded by local government and network operators, it could be partially funded by excavators along the lines of KLIC in the Netherlands, or it could be funded by a level of services model in which some services that might only be used by large organizations would require payment while other services could be free.

Damage to underground utilities represents a significant risk to the public and is a major cause of construction project delays and budget overruns. The NUAR project represents an important step forward in enabling the sharing of information about the location and other information about underground infrastructure that will contribute to reducing the risk of damage to underground utilities during construction.

Key Registry of the Subsurface (BRO) in the Netherlands

In 2015 the Netherlands embarked on a national program supported by legislation and standards to expand the collection and sharing of data about the subsurface. Legislation passed by the States General created the *Basisregistratie Ondergrond (BRO)* or *Key Registry for the Subsurface* which is open and accessible to all citizens of the Netherlands. The law mandated that if you excavate or drill you have to share your data with the BRO registry. In addition if when using the data in the registry you find something is incorrect it is mandatory to to report it.

The Key Registry for the Subsurface (BRO) came into force in January, 2018. The BRO registry forms part of the System of Basic Registrations of the Netherlands which includes location and other data on addresses, buildings, topography and cadastral data. The BRO registry consists of 26 data types, which will become mandatory in installments over five years and all of which include location. On 1 January 2018, it became mandatory to report the first three data types, geotechnical surveys (CPT), groundwater monitoring wells and soil drilling sample profiles. On 26 June 2018, this data became publicly available via the Dutch open data portal PDOK. Work is underway to implement data models for the remaining data types including geotechnics, soils, and groundwater. All 26 will become mandatory by 2022.

Fully automated one call systems

Netherlands and Flanders

On 30 July 2004 at a construction site in Ghislenghien, Belgium a one metre diameter natural gas pipeline ruptured resulting in 24 fatalities, including five fire-fighters, a police officer and five employees, plus 132 injured requiring hospitalization. It caused total devastation within 200 metres in an industrial/agricultural area destroying a cardboard mill, a gas station, and a large number of roofs and cars. A portion of the construction site was damaged and many agricultural fields burned.

In 2007, the first version of KLIP, the Flemish one-call system which is a broker for information about the location of underground utilities, went into production in Flanders. In the Netherlands in 2008 the Subsoil Cables and Pipelines Information Exchange Act (WION) came into effect. The objective of the system is to prevent damages to the utility network and to ensure the safety of excavators during excavations. WION made KLIC, the Dutch one-call system, which had existed since 1967, mandatory for both network operators and excavators with severe penalties for excavators who circumvented the system. Violating WION can entail a maximum fine of € 450,000 for network operators and € 100,000 for excavators. WION obligates all network operators to participate in the system, using a standard information model for registering their infrastructure. The KLIC-online system, which provides on-line information exchange of underground utility information between network operators and excavators, was built and is maintained by the Dutch Kadaster. The Agency Telecom, part of the Ministry of Economic Affairs, is designated as the regulator and enforcer of the act.

In 2010 the Netherlands switched to a digital information system (KLIC-Online). Currently there is a charge of € 32 for every information request. Anyone planning to excavate within the next 20 days is required to go to the KLIC App site and create a polygon enclosing the proposed excavation area (which cannot exceed 500x500 meters). They then click on the type of work: dredging, grub/plan trees, deep ploughing, foundation work, drive piles, gardeners work, place/remove poles/masts, demolition work, pond digging, dam-wall/timbering, drainage, site preparation, place fencing, place cables/pipes, sewerage work, dig or excavate tanks/wells/containers, dig forage hole, or reallocation; enter personal information; and pay. It is important to note that engineering design is not one of the options.

Network operators/managers	1,130
Annual notifications (request for info)	759,000
Annual excavation damage	41,169
Direct costs from damage	€ 34,500,000
Average repair cost per excavation damage	€ 838

For 95% of information requests the excavator will receive an email within one business day with links to digital maps of all underground infrastructure and the names of the utility and telecom operators with facilities in the excavation area. This data can be used both online and offline. The online system allows distances to be measured and provides information about the quality of the location information about underground utilities. For the next 20 days the excavator is cleared to begin excavation unless some of the facilities in the area are high consequence utility lines such as gas transmission and high voltage electric lines. In these special cases the excavator will be directed to contact the network operator for supervised excavation.

Network operators are required to report all incidents of damage to their infrastructure including location, cause and other information. Based on this and other information Kadaster publishes an annual report with statistics on underground utility damage. The following is an example of statistics about underground utility information requests and damage in the Netherlands for

2018.

The biggest benefit of the KLIC system is efficiency. In this respect KLIC seems light years ahead of North America and other jurisdictions where every request for information to a one-call centre results in multiple vans converging on the spot where underground detection tools are used to locate underground utilities whose location is then marked by paint or flags.

On the negative side, the goal of reducing excavation damage has not yet been reached. With tens of thousands of incidents of utility damage every year, there is certainly room for improvement even compared to North America. That this is achievable can be seen by contrasting the number of incidents in the Netherlands with North America and Japan where in 2016 the number of incidents of underground utility damage was dramatically less.

Furthermore, information about the location of underground utilities needs to be available for other use cases than just excavation; first and foremost, the planning and engineering design phases of construction projects (as Colorado has just mandated), but also disaster planning, and emergency response.

Mandated subsurface utility engineering survey and data quality improvement

Colorado 811

Colorado's recent one-call legislation is progressive, especially by requiring mapping of underground utilities prior to engineering design for public civil engineering projects such as highway construction and for providing strong motivation for network operators to improve the quality of the location data for their underground facilities. That a digital or paper sketch or imagery is now required in addition to marking the ground would appear to be a step in the direction of a completely digital 811 system such as KLIC in the Netherlands or KLIP in Flanders.

Colorado's statutes for the prevention of damage to underground utilities were assessed by the federal pipeline authority PHMSA in 2014 and found to be below standard in two areas. As a result the Colorado General Assembly has revised its excavation safety statutes (Article 1.5 of Title 9) to be compliant with current best practices. The latest legislation is progressive. Most importantly, it explicitly mandates subsurface utility engineering (SUE) practice prior to engineering design on public construction projects to determine the location of all underground utilities in the proposed excavation area to ASCE 38-02 quality level B by a licensed professional engineer. (ASCE quality level B requires the application of subsurface remote sensing detection technologies such as electromagnetic detection and/or ground penetrating radar.) Furthermore, the legislation creates an enforcement agency for reviewing violations of Article 1.5 with the power to impose civil penalties.

The report from the National Transportation Safety Board (NTSB) investigation into the 2017 explosion that killed two people and destroyed a home in Firestone, Colorado determined the likely cause was a natural gas leak through a pipeline that had been severed during construction of the home two years earlier. The pipeline was an undocumented gathering line from an Anadarko well that had been officially abandoned, but the gas valve at the Anadarko well for the line had never been turned off.

Figure 1. Photograph of the residence before and after the accident. Photograph on the left was provided by Weld County, photograph on the right was provided by the Pipeline and Hazardous Materials Safety Administration.

In 2018 the Colorado legislature revised its one-call legislation. The latest legislation is progressive, chiefly for four reasons.

1. It explicitly mandates subsurface utility engineering (SUE) prior to engineering design for public civil engineering projects to determine the 2D location of underground utilities to ASCE 38 quality level B by a licensed professional engineer. (ASCE quality level B requires the application of remote sensing detection technologies such as electromagnetic detection and ground penetrating radar.)
2. Prior to the commencement of construction in addition to painting or flagging a proposed excavation site, network owners/operators are required to provide a digital sketch, a hand-drawn sketch, or a photograph.
3. It has provisions to ensure that owner/operators submit complete, accurate and current "as-constructed" drawings recording the location of their underground facilities. It provides for inspections with penalties if the drawings are found to be non-compliant.

4. It creates an enforcement agency for reviewing violations of Article 1.5 with the power to impose civil penalties.

The real teeth in the new legislation for improving data quality by network operators is that it mandates CDOT to conduct quality control as part of construction oversight. Specifically, it requires third party inspectors registered with CDOT and paid for by the network operator to conduct construction oversight to ensure that the "as-constructed" drawings submitted to CDOT accurately reflect what was actually installed in the ground. Various measures including denial of further construction permits and civil penalties can be levied against non-compliant network operators.

The new legislation differs from previous legislation by explicitly making the State of Colorado, through its agency CDOT, responsible for regulating infrastructure installed in the public right-of-way. In practice every network operator that plans to install network facilities in the public ROW, is required to apply to CDOT for a permit. One of the requirements of the permit is that for all newly installed facilities network operators must ensure that the new facilities are locatable, either by marker balls and tracer wire and by an accurate survey. Furthermore, within 45 days of the completion of construction the network operator is required to provide "as-constructed" plans in PDF format to CDOT. The as-constructed document must comply with the ASCE standards 38-02, which specifies quality levels A through D, and 38-20, which specifies seven accuracy levels ranging from Level 1 (XY ± 50 mm, Z ± 25 mm) to Level 7 (indeterminate).

In many states there is no provision as part of one-call legislation for owner/operators to provide information about underground utilities to engineers to assist with the design of civil engineering projects. This often results in the wasteful relocation of utilities. In Colorado it is now mandatory on public civil engineering projects to create a 2D map of underground utilities as part of design. *Subsurface utility engineering-required projects* are public projects that primarily involve horizontal construction, an excavation footprint exceeding 1,000 square feet and two feet in depth and that require the design services of a licensed professional engineer. During the design phase of these projects a licensed professional engineer is required to attempt to determine the location of all underground utilities within the proposed excavation area to ASCE 38-02 quality standard B or better. To assist this process utility owner/operators are required to either provide their available records of the approximate 2D location of their underground facilities or mark the ground in the excavation area .

In most states one-call legislation only requires painting or otherwise marking the ground to show the location of underground utilities. In Colorado now in addition to marking the ground owner/operators are required to provide documentation listing the owner/operator's name, the size and type of each marked underground facility, and a digital sketch, a hand-drawn sketch, or a photograph that includes a readily identifiable landmark. This is a first step toward being able to simply provide an accurate digital map of underground facilities in the proposed excavation area (as is done in the Netherlands and Flanders).

North America, the United Kingdom, Australia and other jurisdictions are characterized by a liability model that puts the onus on excavators to avoid hitting underground utilities. This provides little motivation for owners/operators to improve the quality of their information about the location of underground facilities. In Colorado Article 1.5 appears to alter this general liability model. It states that if the documentation or markings are determined to be inaccurate, the excavator shall immediately notify the owner/operator through Colorado 811 to request an immediate reverification of the location of the underground facility by the owner/operator. The owner/operator is required to respond as quickly as practicable during which time the excavator can continue excavation activity with appropriate caution. Furthermore, Article 1.5 states that if the documentation or markings provided still fail to identify the location of the underground facilities, the excavator is required to notify Colorado 811, but can then proceed with excavation. Article 1.5 states that in this case the excavator is not liable for damage to the owner/operator's facilities except upon proof of the excavator's lack of reasonable care. However, accuracy is not quantified. Later in Article 1.5 where liabilities are discussed, the language relating to accuracy seems less strong. It states that excavators are liable if they fail to notify Colorado 811 of their intention to excavate or fail to exercise reasonable care in excavating. Owner/operators are liable if an underground facility is damaged as a result of the owner/operator's failure to participate in Colorado 811 or by their failure to use "reasonable care" in the marking of the damaged underground facility.

The most important area that PHMSA found deficient in the earlier Colorado damage prevention legislation was that it did not provide for enforcement. The most recent legislation provides for the creation of an Underground Damage Prevention Safety Commission in the Department of Labor and Employment that is independent of Colorado 811. The commission operates independently of Colorado One-call and is composed of six representatives of owner/operators, four representing engineers, contractors and excavators, four representing government agencies and one representing farmers and ranchers. It has two primary responsibilities, Firstly, to advise Colorado state agencies, the general assembly, and local governments on policies and best practices. Its other responsibility is enforcement. It is responsible for reviewing alleged violations of Article 1.5 and can order appropriate remedial action or penalties. Alleged violations are reviewed by a committee convened by the Safety Commission which must include the same number of members representing excavators and owners/operators plus one from another group. A recommendation of remedial action that includes a fine requires a unanimous vote of the review committee. Alternatively a voluntary alternative dispute resolution program is available through Colorado 811 to all owners/operators, excavators, and others regarding disputes arising from damage to underground facilities.

The legislation requires the reporting of damage to underground utilities by members (owner/operators). For each incident the location, duration of service interruption and whether Colorado 811 had been notified prior to excavation must be reported to Colorado 811. However, this is much less information than what is requested by the Common Ground Alliance's voluntary reporting of underground utility damage or PHMSA's mandatory reporting of pipeline incidents. Specifically it does not include fatalities, injuries or costs.

For collecting and maintaining location information about underground utilities CDOT has adopted a hybrid approach that incorporates elements of survey and GIS technology and practices. This approach enables data from disparate sources including surveys, GIS, design files, construction documents, subsurface utility engineering reports, and utility relocations into a shared database managed by a server application (Transparent Earth) that is accessible in the field from a handheld app (Pointman). An advantage of this approach is that it is not only a GIS but enables the capture of survey grade location information.

For new and relocated underground utilities it enables all location information to be captured at survey level including the metadata typically recorded in a surveyor's field book such as when the survey was conducted, who conducted it, the equipment used, and so on.

In the CDOT system all location information has pedigree or metadata associated with it. The system was developed by a private developer Prostar Geocorp. The system is natively built to be open source using GeoServer and seamlessly integrates with other modern technologies such as Bentley and ESRI and legacy systems of record such as GE Smallworld. It uses standard map services such as Google Maps, Bing, and OpenStreetMap for base mapping as well as LiDAR and drone imagery when higher levels of precision are required. The ProStar system leverages Open Geospatial Consortium (OGC) standards including Web Mapping Services (WMS) and Web Feature Services (WFS) and supports quality standards such as ASCE 38-02 and the imminent ASCE 38-20. It offers permissions-based security to protect the data. The Prostar system integrates with Colorado 811 in real-time, making it possible to display the location of all open tickets and their status on a PC or mobile device such as a tablet or smartphone.

The primary goal of the system is to provide easy-to-use access to high quality location data at low cost and to fit into the existing engineering and construction practices of network operators to minimize the learning curve and avoid adding to costs. Pointman is free and offers an affordable handheld solution for small contractors. The Transparent Earth server application is available to network operators, large construction contractors and engineering consulting firms, and government agencies such as CDOT. It enables all stakeholders in a construction project to share data about underground infrastructure.

Another advantage of the system is that it enables survey-grade information to be captured by survey technicians as well as GIS professionals with some additional training in survey technologies.

Colorado's new approach to underground utility information is progressive, especially by (1) requiring mapping of underground utilities prior to engineering design for public civil engineering projects such as highway construction and (2) by mandating the timely submission by network operators or their contractors of accurate "as-constructed" drawings enforced by inspections.

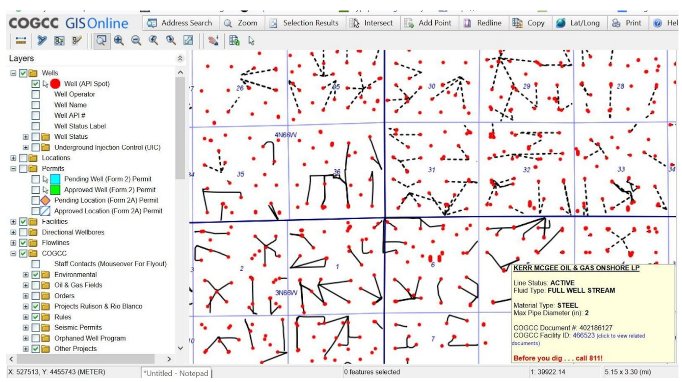
Open mapping of underground oil and gas pipelines

Colorado Oil and Gas Conservation Commission

Colorado is also unique in that it has also recently passed legislation, in response to the Firestone explosion, that requires mapping of natural gas gathering and flow lines. There are nearly a million natural gas and oil wells in the United States, most of which have used fracking to release natural gas and tight oil from underground geological strata. To gather and collect gas and oil from these wells a vast infrastructure of flowline and gathering has been placed in the ground. For the most part this has been unregulated and the location of these pipelines is unknown.

When oil and gas operating companies develop new wells they bury flow and gathering lines to collect products from these wells. The lines consist of miles of unregulated pipe for which the operators themselves may not have exact locations, because the lines are generally considered “temporary use” assets. Once a set of wells was depleted, the gathering lines were abandoned, but remained in the ground.

In April 2019, Senate Bill 181 was passed in the Colorado assembly. It made the Colorado Oil and Gas Conservation Commission (COGCC) responsible for regulating previously unregulated gathering lines. In response to SB-181 new rules adopted by the COGCC late in 2019 required the oil and gas industry to provide maps of their flowline and gathering system infrastructure. Much of this infrastructure had never before been documented or identified.



This rule making by COGCC has major implications for oil and gas companies. In 2013, Colorado had 58,200 miles of intrastate gas pipelines of which about 17,300 miles comprised gas gathering lines. For comparison Texas, which has the largest pipeline infrastructure in the U.S. with over 450,000 miles of pipeline (about 1/6 of the total pipeline mileage of the entire United States), has over 240,000 miles of gathering lines, most of which is currently unregulated. In Colorado the COGCC has collected information on about 7,000 miles of flow lines and has published maps of these flow lines on their website with an accuracy no less than ± 25 feet.

Nationally regulated underground infrastructure information

Pipeline and Hazardous Materials Safety Administration (PHMSA)

Since 2004 the total miles of pipeline in the US including crude oil lines, petroleum product lines, gas distribution mains, gas transmission pipelines, and gas gathering lines increased by about 12 % to 1,830,672 miles in 2017. The Pipeline and Hazardous Materials Safety Administration (PHMSA) was created in 2004 by federal legislation. Pipeline operators are required to submit performance measure reports for pipeline infrastructure covered by integrity management (IM) programs. This includes gas distribution, gas transmission, and hazardous liquids. Operators are required to report all pipeline incidents including the amount of location, volume of product released, number of fatalities and injuries, costs and cause. Since 2005, pipeline operators have reported excavation damage as the cause of 1052 incidents, resulting in 48 fatalities, 195 injuries requiring hospitalization, and $ 481,736,551 of property damage.

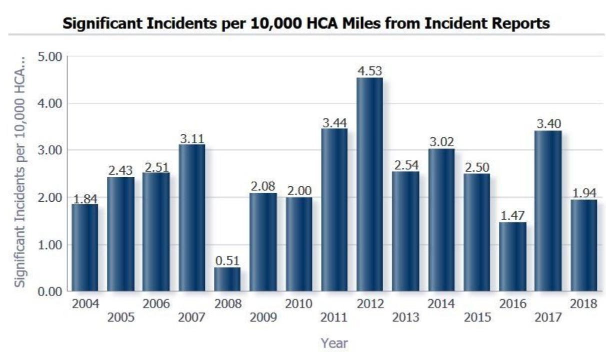
Typical causes of pipeline damage include

- CORROSION - caused by galvanic, atmospheric, stray current, microbiological, or other corrosive action.
- EXCAVATION DAMAGE - incidents resulting directly from excavation damage by operator's personnel, by the operator's contractor, or by people or contractors not associated with the operator
- INCORRECT OPERATION - incidents caused by operating, maintenance, repair, or other errors by facility personnel
- MATERIAL/WELD/EQUIP FAILURE - incidents resulting from poor welds, poor construction, and stresses such as vibration, fatigue, and environmental cracking.
- NATURAL FORCE DAMAGE - incidents resulting from earth movement, lightning, floods and washouts, frost heave, and other natural causes.
- OTHER OUTSIDE FORCE DAMAGE - incidents caused by non-excavation-related outside forces including vandalism and terrorism.
- ALL OTHER CAUSES - incidents whose cause is currently unknown

Since pipeline incident data began to be collected the proportion of incidents attributed to excavation has increased. For example in 2018 34.4 % of gas distribution leaks (unintentional escapes of gas from the pipeline not reportable as Incidents) were caused by incorrect operation. In 2010 only 16.4 % were attributed to incorrect operation. Clearly improved training and other initiatives have reduced equipment operation failures but also being able to better identify causes has made it possible to reduce other types.

PHMSA defines serious incidents as those that include a fatality or injury requiring in-patient hospitalization. PHMSA statistics suggest there may have been some improvement in the number of serious incidents and in fatalities, but propagating these statistics to increased pipeline mileage does not confirm this trend.

On June 10, 1999, a gasoline pipeline operated by Olympic Pipeline Company exploded in Bellingham, Washington. Three people died in the accident. On August 19, 2000 a natural gas pipeline owned by the El Paso Corporation exploded near Carlsbad, New Mexico killing 12 people. After these incidents the government moved quickly to improve the quality of geospatial and other data about underground pipeline assets. Operators were required to identify high consequence areas (HCAs) where there were 20 or more structures intended for human occupancy within a radius (potential impact radius or PIR) defined by the diameter and pressure of the pipe.



One of the reported statistics is the number of significant incidents per 10,000 HCA miles. Significant incidents are defined as incidents involving a fatality or injury requiring hospitalization, $50,000 or more in total costs measured in 1984 dollars, substantial liquid releases, or fires and explosions. The data reveals no trend in improvement in this statistic.

New regulations have been released by PHMSA. Referred to as the Gas Mega Rule the new regulation extends the higher standards of pipeline maintenance to moderate consequence areas (MCAs). Pipeline operators are now required to identify areas where 1) the number of occupied structures within the PIR is five or greater and less than 20 or 2) where any portion of the pipeline PIR intersects the paved area of interstate highways, freeways and expressways and other principal four-lane arterial roads. Operators are also required to report longitude/latitude to five decimal places for all incidents.

Whereas in the past identifying HCAs involved hand drawing building footprints from imagery, machine learning can now be used to automate the process of identifying building footprints prior to using a buffer analysis to identify areas qualifying as MCAs. The analysis is aided by the current accuracy requirement for locating pipelines of ± 50 feet. Identifying MCAs where highways intersect pipeline PIRs is more complex because automating the identification of transportation corridors is more difficult. There are alternative, but more expensive ways to find this information.

An analysis of a 14.91 mi transmission line suggests that the impact of the new regulation will be significant, more than doubling the areas where higher integrity maintenance applies. This creates a significant opportunity for new geospatial technologies including machine learning.

By analogy with the civil aviation industry, reliable statistics resulting from government mandated reporting of pipeline incidents provides the foundation for the next phase of implementing safety management plans designed to produce continuous improvement in these statistics. Safety management systems tailored to specific industries and requirements have been developed often involving regulation for civil aviation, international maritime shipping, and the rail industry in Canada. A current focus in improving is pipeline safety management systems (PSMS), specifically the RP 1173 framework developed by the American Petroleum Institute (API) in partnership with PHMSA, state pipeline regulators, and other interested stakeholders. RP 1173 provides best practices for pipeline operators including operational controls, risk management, incident investigation, evaluation, and lessons learned, and safety assurance. This is intended for operators of hazardous liquids and gas pipelines under the jurisdiction of the US Department of Transportation. It provides for the comprehensive and systematic management of safety-related activities for achieving its goal of zero incidents per year.

The 2017 PHMSA report entitled *A Study on Improving Damage Prevention Technology* found that despite efforts by PHMSA and other stakeholder groups, including pipeline operators, excavators, and trade associations such as the Common Ground Alliance, to improve the practices and technologies, excavation damage remains one of the leading causes of serious pipeline accidents. It made several recommendations, among them improving and implementing GPS/GIS technologies in accurately locating and documenting the location of underground facilities, national standards for state one-call requirements and evaluating and implementing predictive analytic tools,which use data to identify and proactively address high-risk excavations.

France

In 2012 a French presidential decree mandated that all of France's critical underground utility infrastructure be mapped to an accuracy of 40 cm (about 16 inches). According to the decree critical infrastructure includes buried electric power cables, pipelines, and public transport infrastructure, but not buried water and telecommunications infrastructure. The deadline for urban areas was January 1, 2019 and for non-urban areas January 1, 2026.

Responsibility for mapping underground infrastructure

The national regulation requiring mapping of subsurface infrastructure titled Decree relating to excavations near underground, overhead or underwater transmission or distribution networks was promulgated on 15 February 2012. The "anti-network damage" reform, known as "DT-DICT", came into effect on 1 July 2012. (DT is a notice on intended construction work sent by the contractor to the operator of the network. DICT is a notice of intention by the contractor to start work.) It requires owners and managers of critical infrastructure networks to make a commitment about accurately locating their works. The responsibility for implementing the decree lies with a "competent local authority," which is not defined in the decree. Across France different departmental organizations have taken responsibility for implementing the decree. For example, in the Ardèche Département in the southeast of France, the Syndicat Départemental d'Energies de l'Ardèche, the Energy Agency of the Ardèche Département, has claimed responsibility for implementing the decree because it is responsible for electric power distribution and street lighting to the 339 municipalities in the Département and because it has already carried out a cadastral mapping project.

Critical infrastructure

The decree distinguishes critical infrastructure for public safety, critical infrastructure for the economy and non-critical infrastructure. Critical infrastructure for public safety includes

- pipelines carrying liquid or liquefied hydrocarbons, combustible and other hazardous gases, steam, and heated water
- electric power lines and public lighting networks
- public transport infrastructure
- sewer lines under pressure
- flood prevention structures

Infrastructure that is not considered to be critical for public safety include,

- telecommunications cables and low voltage power lines and public lighting network
- drinking water and industrial water supply or fire protection
- sanitary and storm sewers

Telecommunications cables and facilities are considered to be critical economic infrastructure, but not critical for public safety.

Buried networks that are critical according to these definitions and located in urban areas were to be georeferenced in the national system of coordinates with class A accuracy, in other words to 40 cm or better, by 1st January 2019. Implementation of this mandate for all critical infrastructure networks on the national territory of France must be completed by 2026. (*Les réseaux sensibles enterrés, situés en unités urbaines, devront être géo référencés dans le système national de coordonnées en classe A au 1er janvier 2019 et que ces exigences seront applicables à ces mêmes réseaux sur l'ensemble du territoire national à l'horizon 2026.*)

Accuracy of location of underground structures and liabilities for construction projects

Project managers of proposed construction projects are required to send a DT which is a statement of the proposed work including a polygon delineating the area affected to the operators of utility networks operating in the area. In return operators of utility networks must provide the project managers maps of their underground networks in the area indicating the accuracy of the geographical location of different structures of their networks classified according to three accuracy classes.

- **Class A**: *if the maximum uncertainty of location indicated by the utility operator is less than or equal to 40 cm*
- **Class B**: *if the maximum uncertainty of location indicated by the utility operator is greater than that for Class A and less than or equal to 1.5 meters*
- **Class C**: *if the maximum uncertainty of location indicated by the utility operator is greater than 1.5 meters, or if the operator is not able to provide the location.*

The Decree states that uncertainty in the geographical location of a structure is considered likely to jeopardize the construction project or significantly impact the technical or financial conditions of its implementation when the accuracy of the geolocation of the structure is classified B or C. For structures falling in these accuracy classes, the utility operator is required to initiate a process to reduce this uncertainty and achieve class A as quickly as possible.

Furthermore, if further investigation (typically potholing) of some structures by the contractor is required, the cost of the investigations is assigned as follows

- The construction contractor assumes the entire cost when the structures have been assigned by the operator to accuracy class B and further investigation reveals that the actual classification is found to be Class B or Class A
- Half of the cost of the investigation is to be borne by the operator when the structures are assigned by the operator to accuracy class C
- All of the cost is to be borne by the operator when the structures have been assigned by the operator to accuracy class B and when the result of further investigation reveals that the actual classification is accuracy class C

Surveying underground infrastructure for construction projects

For construction project reporting, contractors are required to survey all new and changed underground structures. These surveys must satisfy certain conditions. Location coordinates of structures in an open trench must be surveyed by a certified provider. If remote detection technology such as GPR is employed, the firm performing this work is not required to be certified, but a certified provider must be involved in georeferencing the data. Whatever the method of measurement used , direct or remote, the accuracy of the locations of new or changed structures reported by the contractor must be accuracy class A, in other words 40 cm or better. For each structure the data recorded must include the name of the project manager of the site, the name of the company that provided the location information, the name of the certified provider responsible for determining the location of each structure, the maximum measurement uncertainty (for x, y, and z), and in the case of remote detection such as GPR or EMI, the type of measurement technology used. Presumably this information would be used to assign liabilities in the case that it is determined later that inaccurate location data was reported. This data must be shared with the operator or operators of the networks affected.

Mandated industry supported one call centres

One call in North America

In North America every state and nearly every Canadian province have enacted legislation creating a one call or 811 centre. The one call centre is supported financially by its members. Each utility has to provide information to the centre about the service area where they have underground facilities. They are also required to provide underground locate services. This can be quite expensive because it typically involves dedicated staff and an investment in underground detection equipment and vehicles.

Procedures for locating subsurface utilities

In North America locates, the initial locating (or providing maps of) underground utilities just prior to initiating excavation, is the responsibility of the network operators. Prior to beginning excavation anyone excavating deeper than (typically) 18” is required to call the state or provincial one-call centre and provide information about where and when the planned excavation is to take place. The one call centre, which has maps of each network operator's services territory but does not maintain maps of underground infrastructure, contacts the utilities and telecoms whose service territories overlap the area where the excavation is planned. Within (typically) three business days the network operators are required to mark the ground, either with paint or flags, indicating the approximate location of any facilities they believe they have where the excavation is planned. In Ontario, where the network operators have up to five days to respond, they are also required to provide paper sketches/maps of their facilities. This is all free of charge to the excavator, but entails significant costs to the network operators who are required to support the local one call centre as well as provide locate crews and equipment, either using in-house resources or by contracting the work out to specialized locate companies. Another alternative is that the excavator can contract and pay a commercial locate company to conduct a subsurface utility engineering survey (SUE). There are those who argue the reduction in risk is worth the extra cost, in particular because the commercial locator may find unknown and abandoned facilities that are not shown on network operators' as-builts.

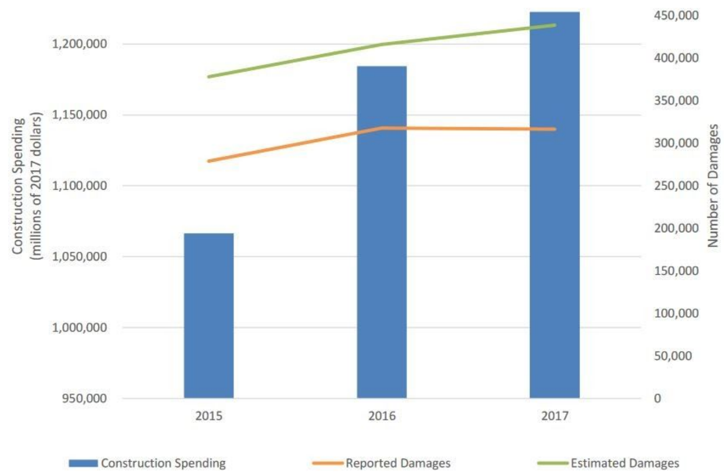
After completion of the initial locate by the network operators identified by the one call centre or by a commercial locate contractor, the excavator is free to begin to dig. The next step for the careful excavator is to verify the location of the facilities, typically by potholing using safe excavation practices such as vacuum or hydraulic and hand tools. Once verification is completed, the careful excavator can continue excavation using traditional machine tools. However, a significant risk of unidentified underground infrastructure remains, which motivates the careful excavator to conduct or contract EMI and/or GPR scans augmented by potholing before beginning machine excavation.

An analysis by Markets and Markets has valued the U.S. commercial utility locator market, including hardware and commercial services, at US$ 1.2 billion in 2017. It projects that the U.S. market will grow at a rate of 5.56 % to reach US$ 1.7 billion by 2023. The global commercial utility locator market was estimated at US$ 5.17 billion in 2017 and growing by about 6% CAGR to reach US$ 7.50 billion by 2023.

Another challenge which is a major issue in Ontario is what is referred to as *late locates.* When network operators fail to locate their underground utilities within three business days (five days in Ontario) after the one-call centre notifies them, they are legally subject to civil penalties. In some jurisdictions such as Ontario, late locates are a significant problem because the legal requirement of five business days is seldom enforced with the result that projects are frequently delayed. It can also lead to increased risk of utility damage if frustrated contractors with tight deadlines decide to proceed without locates.

It is interesting to contrast the North American experience to Australia and New Zealand where locates are entirely the responsibility of the excavator. The excavator is required to select a locate company from a list of certified locators to conduct the locate, and to pay for the locate. Apparently there was a pilot of this approach in Alberta, Canada that was assessed as very successful because there was no utility damage recorded during the pilot.

In the U.S. the Common Ground Alliance (CGA) has been collecting voluntarily submitted statistics on underground utility damage since 2003. The latest CGA DIRT report for 2018 concluded that progress in the U.S. in reducing damages has plateaued. Total damages in the U.S. increased from 439,000 in 2017 to 509,000 in 2018, representing a 16% increase. Damages per 1,000 one call information requests increased by 11%, from 1.87 to 2.08, and damages per million dollars of construction spending (2017 constant dollars) went from 0.359 to 0.392.



Florida one call

In Florida, the Underground Facility Damage Prevention and Safety Act enacted in 2017 by the Florida legislature is typical of the legislation creating state one-call centres. It mandates that every organization with underground infrastructure is required to be a member of the state one-call centre. After being contacted by Florida One Call utility operators have two days to visit the proposed excavation site to mark using stakes, paint or flags where they believe their facilities are. The Florida act stipulates that these markings identify a corridor 4 feet wide within which a utility cable or pipe is expected to be found and that they conform to a standard for colour code for markings. The law also provides an option for a utility operator to state that it believes it has facilities in the area but is unable to identify where they are. This option is only available for abandoned facilities or for facilities that are not detectable with the available technology.

Typically each utility and telecom operator contacted will dispatch locate staff equipped with current as-builts, electromagnetic wands and/or ground penetrating radar to detect and mark where their networks traverse the site. After all the network operators with facilities in the areas have done this, the excavator is free to begin excavation. If a network operator has stated that it can't identify the location of its facilities, the Florida act requires the excavator to use underground detection tools to attempt to identify any underground facilities. The excavator is free to dig using machine tools outside the marked utility corridors. To dig within the corridors, the Florida act stipulates that soft digging techniques must be used.

Liabilities work as follows:

- If after the network operators identify the location of underground facilities, an excavator causes damage, the excavator is liable for the total sum of the losses to all parties involved to a maximum of $500,000 per underground network.
- If a network operator does not mark the location of its facilities after being contacted by the One-Call system and an excavator damages the underground network, the excavator is not liable for the damage and the network operator is liable for any injury to a person or to equipment to a maximum of $500,000.
- If the network operator isn't able to identify the location of its facilities in the excavation area, the excavator is not liable for any damages that might occur.

But there is a proviso on this: An excavator must excavate in a "*careful and prudent manner, based on accepted engineering and construction practices, and it does not excuse the excavator from liability for any damage or injury resulting from any excavation or demolition.*" Furthermore, if the network operator is unable to identify the location of its facilities in the excavation area, the act stipulates that the excavator must use subsurface detection tools to try to identify the location of the infrastructure.

At a high level the liabilities are pretty straightforward, but in practice there is plenty of room for litigation. A recent example of what can happen when unknown utilities are encountered during construction is the 405 Freeway widening project in Los Angeles where workers had to remove nine miles of unexpected utility lines which contributed to delaying the project a year behind schedule and resulted in a $400 million lawsuit.

The other important aspect of this legislation is that it does not require the information discovered about underground utilities to be shared. It is not the responsibility of the one-call centre itself to manage this type of information. The act does not mention maps, paper or digital, to be provided by the network operators nor does it require utility location information discovered by the excavator to be shared with the network operators. Over time there is little in this act that would lead to an improved 3D map of underground infrastructure.

In addition to improved safety to the public and construction workers, there is a financial motivation for a utility or telcom to improve the quality of its mapping of its underground infrastructure. A not insignificant cost incurred by a utility supporting this liability structure is the maintenance of a fleet of cable locate vans, equipment and staff. A utility can reap significant cost savings by reducing the size of this fleet by improving the quality and timelines of the information about the location of their underground infrastructure. For example, I worked with a power utility in Calgary that had over twenty vans dedicated to cable locates. Calgary, in a very forward looking move, had passed an ordinance that required that all utilities and telecoms operating within city limits share maps of their underground networks as part of Joint Utility Mapping Partnership (JUMP). The maps had to be submitted in digital form, DGN files at the time. Under the impetus of the city ordinance, the utility I worked with decided to change their facilities records workflow to improve the quality and timelines of their data so that the maps they made available through JUMP were accurate and uptodate. To do this required changing the data flow from network engineering to their GIS. All of their engineering data was stored in a spatially-enabled relational database which enabled them to shorten the cycle from engineering to GIS and ensure that records backlogs were very short, on the order of a day. One of the important benefits of JUMP and the improved data workflow was that the utility reduced its fleet of more than 20 locate vehicles to two, freeing up staff for other activities and saving several hundred thousand dollars annually.

The North American model often results in unnecessary utility relocations. For example, in the traditional approach to highway design, the designer ignores utilities during design. After design and right-of-way acquisition, just before construction begins, the one-call centre is notified and the affected utilities would visit the site and mark the location of their underground facilities. If utilities conflict with the design, they have to be relocated. As a result utilities are routinely relocated, often at great expense and often unnecessarily. A better approach is to design the highway in a way that takes into account where utilities are located to minimize relocations. But this requires accurate maps of underground utilities during the planning and design phase, not just prior to construction.

In spite of these motivations for better information about the location of underground infrastructure, the liability structure in North America, which effectively limits risk for network operators, has historically not provided a strong motivation for utility or telecom operators to implement procedures to improve the quality of this information. The North American underground locate industry is estimated to be worth $10 billion annually. If the information about the location of underground utilities captured by this industry were shared, it would be expected that our knowledge about the location of underground infrastructure would gradually improve, the risk to the public and workers and the drag on the economy associated with underground utility hits would decrease, the cost of utility locates to utilities and telecoms would decrease, and fewer utility relocations would be required during construction.

Ontario one call

Ontario One Call is an example of a provincial one-call centre currently operating in Canada. In Ontario every municipality, utility, communications company and others with underground infrastructure are required to become members of Ontario One Call which is a not-for-profit corporation. All members are required to provide Ontario One Call with information that describes where the member has underground infrastructure. This typically takes the form of maps showing service territories, and not necessarily maps showing the actual location of underground networks. Anyone planning to excavate within the province is required to contact the one-call centre which is responsible for identifying and contacting all of its members that may have infrastructure in or near the area of the planned excavation. Upon being notified of an excavation potentially affecting its infrastructure each member is required (at no cost to the excavator) to locate any infrastructure it may have that would be impacted by the planned excavation. In Ontario a utility operator is required not only to mark on the ground the location of its underground infrastructure but also provide a written document containing information describing the location of the underground infrastructure. This differs from many one-call centres in North America where a written document is not required.

An important effect of this legislation is that each utility and communications operators maintains a fleet of field staff with vans and locate equipment or contracts a locate service to provide the service. For a utility operating in a medium-sized city this can easily amount to something on the order of a million dollars annually.

The Ontario Regional Common Ground Alliance (ORCGA) has been collecting voluntarily submitted data on underground damage incidents since 2005.While some would argue that this represents only 50% of actual incidents, this is the best compilation of data on underground utility damage in Ontario. It is relied on by Ontario One Call for measuring performance toward its legislated goal of reducing underground utility damage.

The key metrics that are used by ORCGA and Ontario One Call are number of incidents per notifications and number of incidents per information request. Requests are to Ontario One Call and originate from excavators planning to dig. Notifications go to network operators originating from Ontario One Call in response to requests.

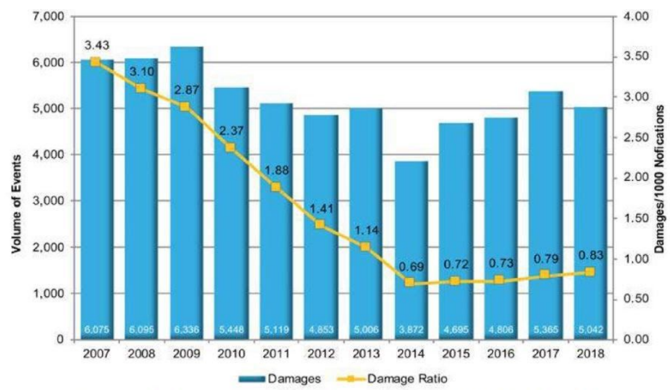


Figure 17: Damage Ratio- Damages/1000 Notifications

The damage ratio for the number of incidents per 1000 notifications since 2007 reveals a decreasing trend through 2014. Since then the trend has been gradually increasing. Similarly the trend in the number of incidents per 1000 requests also decreased from 2009 through 2014, but the trend has been increasing since 2014. The 2018 damage to request ratio shows a decrease apparently reversing an upward trend from 2014. This is the result of a change in the Ontario One Call process which reduced notifications by 10%.

This trend suggests that a more comprehensive approach to safety including regulation, policies and technologies is required to begin to bring the annual number of incidents down.

British Columbia one call

British Columbia is the only jurisdiction in North America that I know of where it is not mandatory for each member (network operator) identified by the one call centre to visit the site of a proposed excavation. In response to a request from British Columbia One Call, within three business days each network operator is required either (1) provide plans (paper or digitally, typically a PDF or paper) of their underground services showing the location of their facilities on or near the excavation site or (2) visit the site to physically mark the location of their facilities, or provide digging instructions and other safety information.

This can be very efficient for network operators because, similar to the Flanders KLIP and Dutch KLIC systems, it is not mandatory for each network operator to maintain a large fleet of locate vans to visit the sites of all proposed excavations. On the other hand, it puts the onus for conducting an onsite locate on the excavator.

Public Services and Procurement Canada

In many jurisdictions in North America in response to a notification of intention to excavate network owners are only required to paint or otherwise mark the ground. Most one-call legislation does not require a written record. At the federal level in Canada an important program has been initiated by Public Services and Procurement Canada (PSPC) for the protection of underground infrastructure on Federal land and infrastructure regulated by the Federal government. It offers the alternative of only providing a digital or paper map of underground infrastructure in the area of the proposed excavation. The PSPC initiative is intended to be a model for all Federal ministries and regulatory agencies responsible for underground infrastructure.

In 2012 the Canadian Common Ground Alliance (CCGA) released a white paper, *Damage Prevention Legislation Elements Required for Canada*, articulating a series of principles and specific elements for effective legislation that would result in greater protection of underground infrastructure and community safety. In the same year Bill 8, the Ontario Underground Infrastructure Notification System Act 2012, was passed in the Ontario Legislature. In 2015 CSA Z247 the first Damage Prevention Standard in Canada was released. It describes the damage prevention process and elements would reduce damages to Canada's underground infrastructure improving public, worker and community safety and preserving the environment and was sponsored by the National Energy Board (now Canadian Energy Regulator), Natural Resources Canada, the Canadian Energy Pipeline Association and the Canadian Gas Association. In 2014 the Senate Standing Committee on Energy, the Environment, and Natural Resources completed two studies; Moving Energy Safely: A Study of the Safe Transport of Hydrocarbo*ns by Pipelines, Takers and Railcars* and Digging Safely - *One Call Notification Systems and the Prevention of Damage to Canada's Buried Infrastructure. The* Senate Standing Committee followed this with specific recommendations;

1. That the federal government references the CSA Z247 standard for protection and prevention of damage to buried infrastructure and encourages provinces and territories to reference the standard in legislation.

2. That buried facilities on federal land be registered with a provincial or territorial one-call service and that the federal government should require anyone undertaking excavation on federal land to call the local one-call centre.

3. That the federal government should require all owners of federally regulated buried infrastructure to become members of a provincial or territorial one-call service.

In its 2016 report on the state of our knowledge about the location of underground infrastructure in Canada, the Professional Surveyors Canada working group concluded that underground infrastructure in Canada is often not surveyed or mapped accurately, if at all. Currently the systems in Canada dealing with underground infrastructure are a patchwork of regulatory and voluntary regimes. They range from the City of Edmonton which maintains a database of underground infrastructure and the City of Calgary that mandates that information about underground infrastructure be shared among utilities and communications firms operating within city limits, through to one-call centres operating in the provinces of British Columbia, Alberta, Saskatchewan, Ontario and Quebec, and others.

The Professional Surveyors Canada working group is very clear about the problems with the current regulatory regimes and business practices in Canada; creates loss of use situations to critical infrastructure such as telecommunications; creates hazards for workers; creates inefficiencies in locates for customers; reduces efficiencies and productivity of one call systems; increases cost for new development; increases cost for each new installation of underground infrastructure; greatly increases the amount of redundant locates being done; increases risk to the public; and increases risk to the environment.

At the federal level Senate Bill S-229, which was introduced in 2015 and passed third reading in the Senate in May 2017, aimed to create a notification mechanism for underground infrastructure on federal lands and for federally regulated underground infrastructure. It would have required that federal agencies register with provincial or territorial one-call centres and develop the capacity to respond to requests for information from one-call centres. Furthermore it would have required that federal regulators of buried infrastructure to develop a damage prevention mandate. But at the time, there was not an appetite in the Government to act on this bill and it died on the order sheet in the House of Commons and never became law.

However, it turns out that the objectives of S-229 did not die there. Two years ago the Minister of Public Services and Procurement (PSPC) decided to implement the provisions of S-229 within PSPC. PSPC is responsible for all infrastructure on Federal land and the Minister saw this as a way of doing a better job at what it is mandated to do.

The long term plan is for the PSPC implementation to become a model for other government departments which would see the benefits of this approach to reducing damage to underground utilities and implement similar measures. There are about a hundred departments and agencies in the Federal government, of which 23 are custodians of real property assets. PSPC, National Defense and Parks Canada are the largest.

Under this initiative implementing protection for buried assets through the existing operational framework for federal custodial assets requires that buried assets on federal land be registered with a provincial or territorial one-call services; and that the federal government require anyone undertaking construction or excavation on federal land to call the local one-call or damage prevention service. Secondly, the federal government requires all owners of federally regulated buried infrastructure to become members of a provincial or territorial one-call or damage prevention service.

To be able to respond to requests for information requires the Federal government to develop and maintain maps of its underground infrastructure through its geomatics capacity. To do that requires determining what information it intends to share taking into consideration Government of Canada security requirements.

The first stage of the PSPC initiative is the National Capital Area (NCA). It requires first of all compiling maps of existing Federal underground infrastructure enabling the government to respond to information requests. Secondly it requires that Federal agencies and owners of Federally regulated infrastructure to register with provincial and territorial one-call centres. In the case of the initial NCA project this means registering with Ontario One Call.

When Ontario One Call receives a request for information about underground utilities for a proposed excavation, PSPC as the custodian is notified. In the case of a proposed excavation PSPC then does one of the following

1. Provides a digital or paper map of underground infrastructure in the area of the proposed excavation
2. Carries out a subsurface survey and marks the ground
3. Confirms that there is no infrastructure in the area

In the case of a request relating to a planning activity PSPC should provide a digital or paper map of underground infrastructure in the area of the proposed excavation or confirm that there is no known infrastructure in the area. It is interesting that this process requires that if information about the underground infrastructure in the area is missing or incomplete, the PSPC is required to conduct a subsurface survey of the area with the resulting map provided to the Federal Geomatics site. This enables PSPC to respond with accurate maps of the area the next time an information request is received. Over time this process would lead to comprehensive geospatial data on underground infrastructure on the Federal Geospatial site.

The immediate goal is to develop a PSPC Directive, Standard and Guidelines for the protection of underground infrastructure. This requires engaging with provincial and territorial one call centres, developing the capability to respond to requests for information, and developing business processes to improve the accuracy, timeliness, and comprehensiveness of the data about underground infrastructure that is maintained by the Federal Geomatics group.

The longer term goal is for Treasury Board to encourage custodians of real property assets assets such as National Defense and Parks Canada, as well as regulatory agencies including Transport Canada, Canada Energy Regulator and Innovation, Science and Economic Development (ISED) to adopt similar policies so that this approach to damage prevention becomes pervasive in the Federal government.

This is an important initiative that provides a model for other Federal departments, agencies, and regulatory bodies. As a federal initiative it also provides a model for provincial, territorial and municipal governments, and regulatory agencies and network operators. Perhaps more importantly it signals just how important this is for public safety and for the Canadian economy.

While the PSPC initiative is an important step forward, there is an important area that it does not address explicitly. The quality of the information about the location of underground utilities maintained by many operators, typically captured from as-builts, is low. To begin improving this information requires some mechanism for sharing the results of on-site locates and the location of underground utilities exposed during construction - potentially by uploading the location of underground infrastructure in digital form to a shared database.

To begin to address these issues the Professional Surveyors Canada report recommends requiring that all new underground infrastructure be surveyed and mapped in 3D with high precision and reliability and sharing basic information on the type, location and depth of underground infrastructure in a standardized form through a common, accessible system. Furthermore, all underground infrastructure surveyed should be in a common format that can update a master map/GIS data set. Such a master database would limit visibility of networks in such a way that sensitive information would not be accessible to competitors (especially important for communications firms) or to others for privacy or security reasons.

A major challenge is finding a way of capturing information about the location of underground utilities accurately and efficiently without impacting construction budgets and schedules. Modern technology offers ways of reality capture that are accurate and efficient. Experiments have shown that modern geoprocessing in the cloud makes it possible to capture the required location information about underground utilities with mobile LiDAR, ground penetrating radar (GPR), combined mobile LiDAR and GPR, consumer digital cameras or smart phones obviating the need for professional surveyors to actually be onsite. This would reduce the impact on construction budgets and schedules.

Private one call system

One call in England

England does not have legislation mandating a one-call centre as just about every state and province in North America does. This puts the onus on excavators to track down and contact utilities and others who may have infrastructure in the area of the planned excavation. To fill the gap a private company LinesearchbeforeUdig (LSBUD) offers something similar to a North American one-call centre. LSBUD offers a voluntary free to use service which anyone planning excavation can use to check for underground utility assets that LSBUD's 75 members (network operators) have in the area of the planned excavation.

The way this works has some similarities with a North American one-call centre. The excavator provides details of the planned excavation to an online system. The system immediately responds with a list of LSBUD members that have assets near where the excavation is planned. Subsequently each member sends plans of their infrastructure assets in the area of the planned excavation.

LSBUD is owned by Fisher German LLP and PelicanCorp, an Australian company that runs one-call centres in Indiana, Kentucky, Alberta, British Columbia, New Zealand, Australia, Ireland, Singapore in addition to the UK. The assets that LSBUD's members manage include hundreds of thousands of kilometers of underground and overhead electricity, gas, high pressure fuel, water and fibre optic pipes and cables. LSBUD is supported by its members which include all fuel transmission companies, 60-70% of electric power network operators, and some water and telecom operators in England. (digdat (Anglian Water Services) is another one call system in England which is primarily focussed on underground assets of water utilities.) The benefits that the members derive from LSBUD are improved safety and reduced utility damage costs. The public also benefits from fewer outages. The LSBUD service processes over 2.5 million inquiries per annum.

There are risks of sharing information for both commercial (competitive) or security purposes. To manage this balance, the Member always controls who accesses their data. Members always control who accesses their data. Users can get very high level information about a Member’s network through the LSBUD oce call process, but members are in full control of the access rights to their detailed information. They also have a live view of those requesting and receiving their information together with a detailed audit trail.

Much of the liability is on the contractor to locate the assets on site. In terms of the accuracy/ validity of the data, the asset owner carries that themselves with relevant disclaimers. The asset owner determines both the Area of Interest (AOI) on the service, as well as any guidance/literature/disclaimers that are sent with their responses.

Municipal projects for managing underground infrastructure

Calgary, Alberta

Years ago the City of Calgary implemented a by-law that is designed to share information about underground utilities and improve the quality of this information. The by-law requires all network operators with underground infrastructure under public rights-of-way to submit to the city electronic as-builts showing the location of newly installed network equipment.

A number of years ago I did some work with a Calgary electric power utility involving replacing a paper-based records management system with one in which all geospatial data was stored in an Oracle RDBMS. As a result the utility reduced its as-built and update backlogs to 24 hours. This made it possible for the utility to provide up-to-date cable location information to the City of Calgary - referred to as Joint Utility Mapping Project (JUMP). At that time the utility realized significant benefits from the shared underground utility information. First of all, improved quality of service. A concrete example that every utility or telco can relate to is one-call. Prior to implementing their geospatial system, the utility maintained a fleet of 20 or so vans and roughly the same number of staff whose sole responsibility was cable locate which involved going out to the sites of a proposed excavations to identify where electrical cables and other infrastructure were to help excavators avoid damaging them. Before the JUMP shared database for every 1000 calls they received from contractors planning to excavate, on average there were nine incidents of damage or "hits", where the excavator dug up a cable and caused a power outage. After the JUMP implementation, the "hit" rate dropped 36-fold to 0.25 per 1000 calls. In addition because there was a single JUMP data store containing the location of all facilities in the city, they were able to reduce their cable locate fleet to something like two vans instead of 20, which saved the utility a not inconsiderable amount of money. Secondly, the electric power regulator in Alberta was much happier because they saw an improvement in the quality of the utility's facilities data. Every year they required utilities to undergo an audit, where an independent auditor took a sample of facilities data out into the field and compared it with reality. The auditor reported something like 99.6% reliability, which is remarkable given that 70-80% is more typical of the industry.

I have just had a chance to go through the latest amended version of the city Bylaw (17M2016 with amendments in 2017 and 2018) the relevant details of which I thought it would be worthwhile to share. The purpose of the Bylaw is to define how a network operator can access City rights-of-way such as roads for purposes of constructing, maintaining or operating its equipment including telecommunication, electrical, natural gas, steam, water wastewater and stormwater facilities and pipelines.

The Bylaw includes provisions with some similarities to other jurisdictions in North America regarding existing infrastructure. A network operator is required to provide the 3D location, line and elevation of its equipment on public rights-of-way to the City within 5 business days of receiving the request from the City. If requested, the network operator must physically identify the location of its equipment by marking the service corridor and using paint, staking or another suitable method for identification.

The unique and interesting parts of this bylaw relate to new infrastructure. It requires submission of electronic as-builts by network operators, provides for on-site inspections to verify the as-builts, and assigns costs and liabilities for underground equipment whose location as reported in as-builts is unreliable.

The bylaw requires that each network operator submit as-built drawings in electronic format, typically DWG files, to the City within 60 calendar days following completion of installation of its equipment on a public right-of-way. The as-builts are required to comply with two key provisions

1. The equipment is less than 35 centimeters horizontally and vertically from the centre line approved in the *utility alignment permit*
2. It adheres to the CSA S250 quality standard.

The City reserves the right to carry out on-site inspections the cost of which is shared between the network operator and the City. The network operator is required to give the City 3 days' notice prior to completion of work to allow for scheduling of the inspection. If during an inspection (or at any other time) the City identifies deficiencies in the network operator's compliance, the City can declare the equipment non-compliant. The City can then take steps to ensure the network operator does whatever is necessary, at the network operator's cost, to bring the equipment into compliance. Specifically a network operator must pay for 100% of the direct costs for relocations of non-compliant equipment as well as indirect costs including any damages, liabilities, re-design costs and associated delay costs incurred by other participants in a public right of way resulting from the network operator's non-compliant equipment.

I see this as a model for any jurisdiction that wants to improve the reliability of the information about the location of underground utilities in public right-of-ways.

Bern, Switzerland

In Bern an online web-based system *Koordination im öffentlichen Raum* was developed primarily for coordinating street works. It is location aware and enables planners to avoid serial excavations of the same stretch of street or road by coordinating all construction from multiple agencies including Federal, Kantonal and city street and highway agencies, water/wastewater, gas, and electricity utilities, and telecommunications companies so that a section of street or road is not dug up more than once every five years.

The City of Bern typically spends between SFR hundreds of million annually on construction for public infrastructure. The initial phase of the coordination system cost about SFR 150,000 and in its first year of operation it was estimated that the coordination system saved SFR 7 million. In other words the project paid for itself in about a week. The initial implementation of the system, developed by Condesys, was deployed in 2000.

In 1999 regulations were passed by the city government requiring coordination among stakeholders involved with public infrastructure. Basically the bylaw specified that all excavation on public property within city limits required a permit. Stakeholders include the city electric and water utility (Energie Wasser Bern or EWB), Swisscom, UPC Cablecom, Colt Telecom, two railways (SBB and BLS), the Postauto bus system, billboard advertising companies, environmental agencies, archaeological agency, the agency responsible for public monuments, the garbage collection department, fire, police and emergency agencies, Kantonal public works, and the Federal Highways Agency (Bundesamt für Strassen or ASTRA). What this means in practice is that all projects involving a certain road or stretch of highway are coordinated so that they all happen at the same time. After completion of construction there is a moratorium on any further excavations on the same stretch of street or road, except for emergencies, for five years. It also means that everyone who is affected by street work from garbage collection to billboards to city planners is aware of when and where construction will occur.

In Bern city bylaws require that anyone planning a construction project involving excavation has to submit information about the proposed construction to the online coordination system. Providing reliable information about the location of underground infrastructure is the responsibility of the organizations operating the infrastructure.

In Switzerland each utility and telecommunications company is responsible for maintaining records that show the location of their underground infrastructure. In Bern they are required to provide the location of their underground facilities to the City Survey Office (Vermessungsamt der Stadt Bern) which is responsible for aggregating the data from the multiple utilities and telecommunication companies into a single database (Leitungskadaster) and making it publicly available.

As in many parts of the world the data quality of this underground geolocation information is an issue. Utilities and telecoms are currently working to improve the quality of their geospatial information about their underground facilities. Swisscom has resurveyed their infrastructure and other utilities have conducted similar projects.

The city has also put in place regulations to ensure that accurate data is captured for new construction projects involving underground infrastructure. For example, there is a 24 hour rule that requires a contractor to notify the city survey department 24 hours before closing a trench. For large projects city surveyors periodically verify surveys of underground works.