SUSTAINABILITY SOLUTIONS USING TRENCHLESS TECHNOLOGIES IN URBAN UNDERGROUND INFRASTRUCTURE DEVELOPMENT

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ABSTRACT: Underground infrastructure systems provide essential public services and goods through buried structures including water and sewer, gas and petroleum, power and communication pipelines. The majority of existing underground infrastructure systems was installed in green field areas prior to development of complex urban built environments. Currently, there is a global trend to escalate major demand for underground infrastructure system renewal and new installation while minimizing disruption and maintaining functions of existing superstructures. Therefore, Engineers and utility owners are rigorously seeking technologies that minimize environmental, social, and economic impact during the renewal and installation process. Trenchless technologies have proven to be socially less disruptive, more environmentally friendly, energy conservative and economically viable alternative methods. All of those benefits are adequate to enhance overall sustainability. This paper describes effective sustainable solutions using trenchless technologies. Sustainability is assessed by a comparison between conventional open cut and trenchless technology methods. Sustainability analysis is based on a broad perspective combining the three main aspects of sustainability: economic; environmental; and social. Economic includes construction cost, benefit, and social cost analysis. Environmental includes emission estimation and environmental quality impact study. Social includes various social impacts on an urban area. This paper summarizes sustainable trenchless technology solutions and presents a sustainable construction method selection process in a proposed framework to be used in urban underground infrastructure capital improvement projects.

Keywords: Trenchless technology; sustainability; underground infrastructure; utility

1. INTRODUCTION

Most urban environments in developed countries experience tremendous challenges during underground infrastructure renewal, expansion, and installation projects. Continuous capital investment in underground infrastructure systems is essential to maintaining satisfied levels of essential public services including energy transportation and distribution, water distribution, sewer collection, and communication systems such as fiber optic lines. Public perception in many developed countries tend to be misguided in that the essential public utility services through underground infrastructure systems have been granted and will last indefinitely. The value of modern underground infrastructure systems are often underestimated and left with inadequate maintenance until failure. Majority of the underground infrastructure systems were developed after World War II in major urban centers. Considering original designed life expectancy, many existing underground infrastructure systems are approaching their maximum useful life and keep structurally deteriorating over time due to aging. In addition, continuous population growth and urbanization require continuous service expansion. Traditional open cut is still the preferred underground construction method by many utility owners, engineers and contractors. Open cut has its own limitations from such as causing unavoidable disruption to surface public activities and premature deterioration of existing structures around the open cut project site. This method is the most suitable method in a Greenfield environment prior to any substantial superstructure development. Recognizing all of these problems; engineers, contractors, and owners are now seeking out viable alternatives to minimize disruption, negative impacts, and maximize benefit especially in urban built environment.

Trenchless technologies have proven to be socially less disruptive, environmentally friendly, energy conservative and economically viable alternative methods through their rich history of successful applications. Many benefits of using trenchless technologies follow the fundamental concept of sustainable infrastructure development, which is based on the triple bottom line approach. This concept includes economic, environmental, and social considerations while still satisfying owner and engineer project objectives and ensure short and long-term benefits to a broad range of society, ecosystems, and industrial boundaries. This paper summarizes sustainable trenchless technology approaches and proposes a framework that can be used to select the most sustainable underground infrastructure construction method.

2. BACKGROUND OF TRENCHLESS TECHNOLOGIES

Trenchless technologies have emerged from various places such as crude oil exploration, chemical polymeric resin development, and an ingenious idea. The trenchless industry has continuously introduced new ideas and advanced technologies in the underground utility construction, renewal, and O&M industries. There are proven benefits over traditional open cut construction methods. The major advantage of trenchless technologies is minimized disruption during underground infrastructure renewal and installation. Minimum disruption leads to other advantages including: 1) minimized socially related indirect costs; 2) being environmental stewards; 3) conserving fossil energy consumption; 4) providing economically viable alternatives; 5) minimizing social and cultural impacts; and 6) ensuring existing structural integrity.

Figure 1 illustrates a classification tree for major trenchless technologies. The family of trenchless technologies is divided into three subcategories including: 1) asset management; 2) renewal; and 3) new installation. Asset management includes pipeline condition inspection and assessment technologies that provide accurate structural condition and operational status. Pipeline condition assessment provides an evidence-based engineering judgment regarding whether a specific pipe needs rehabilitation, replacement, or complete new installation.

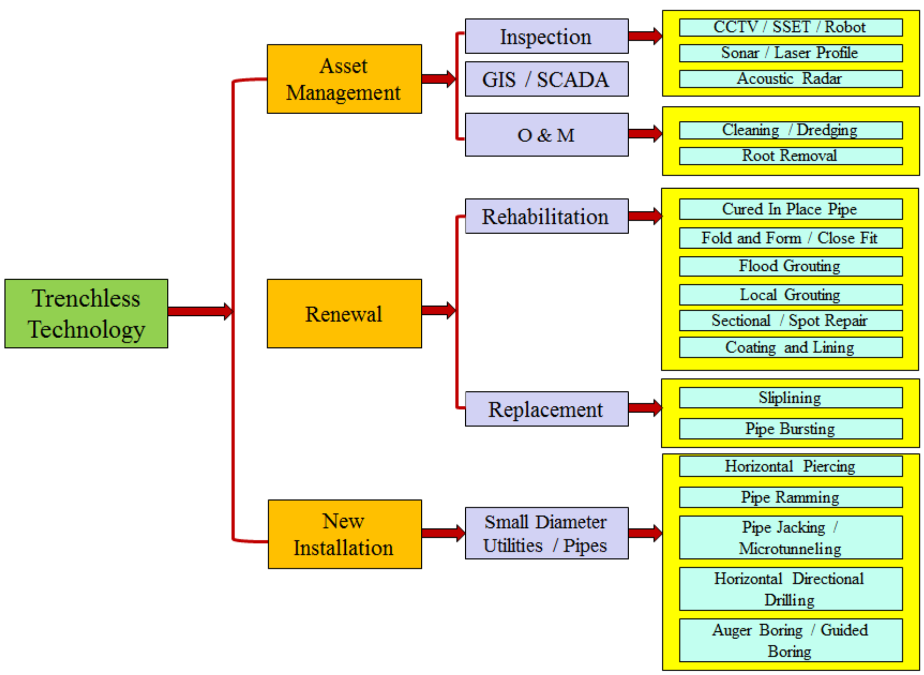

Figure 1. Trenchless Technology Classification Tree

Renewal methods use the existing pipe structure as a means of host structure or passage for installation of a new structure. Some renewal trenchless technologies are selected to extend useful service life. For example, semi or full structural lining methods including Cured-in-Place Pipe (CIPP), Fold & Form, and Close-fit; are installed with various types of lining materials inside of an existing (or host) pipe. Polymeric resin coating and lining methods are used mainly for potable water main rehabilitation to prevent further corrosion and improve water quality. Pipe bursting is a trenchless method that provides a completely new pipe along the same horizontal alignment as the existing pipe. It is the only method capable of upsizing an existing pipe diameter and replacing it with completely new pipe. Sliplining installs a new pipe inside of an existing pipe and may involve grouting of the annular space. The spiral wound method is a structural lining method using continuous winding narrow strips inside of an existing pipe. Many rehabilitation methods in the U.S. are only approved for sewer application and not NSF 61 certified for potable water applications. As compared to sewer application technologies, limited options are available for water main rehabilitation. Today, new methods such as CIPP for water mains and in-situ polymeric lining are continuously being developed and introduced in the water industry. Further information on rehabilitation methods can be found in Sterling et al. (2009).

Most new installation technologies are rooted from traditional boring and mechanical tunneling methods. These techniques have been modified and developed to meet specific installation requirements. The capability of steering and alignment control is a key function to use in utility installations, especially for gravity sewer applications because of a low tolerance of slope change. Technologies such as microtunneling (MTBM), pipe jacking, and guided pilot boring (auger boring) methods can be employed for both new gravity sewers and pressurized force main installations. Horizontal directional drilling (HDD) has been successfully implemented for installation of various pipelines including pressurize pipes such as natural gas, petroleum product pipelines, potable water mains, and sewer force mains. HDD is especially suitable for crossing beneath water course such as lakes, rivers, and streams. Further information on new installation methods can be found in Najafi (2005).

3. SUSTAINABLE UNDERGROUND INFRASTRUCTURE SYSTEMS

3.1 Concept of Sustainable Infrastructure Systems

In general, sustainability is based on a broad perspective combining the triple bottom line components of sustainability. For example, economic aspects include cost/benefit and social cost analysis. Environmental aspects include emissions estimation and a conventional environmental impact assessment study. Social aspects include social disruptions to the general public caused by a project. The concept of a sustainable infrastructure system has emerged from various engineering societies after introduction of the sustainable development concept from the Brundtland report in 1987. The Brundtland report defined sustainable development as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). Sustainable infrastructure systems include not only long-term impacts from an infrastructure project, but also short-term impacts during construction phases. Koo and Ariaratnam (2008) proposed a sustainability assessment analysis method comparing an open cut and a trenchless technology method in a municipal application. Short-term impacts are the main indicators used in the study; however, several long-term impact indicators such as environmental impact, natural resource and fossil fuel consumption, public and worker safety can be both long and short term impacts. From the broad perspective of sustainability, any perceivable impacts potentially caused by a project should be included in an assessment. Achieving a level of sustainability in a project is a part of continuous effort to enhance global sustainability and the impact extends its scope over other industries; thus any effort towards sustainability for an infrastructure project will eventually elevate global sustainability through a scaled effect. Adaptation of sustainability in an underground infrastructure project asks many practical questions. Selection of the most expensive, durable and advanced technology may enhance overall service life expectancy and quality; however, there is a breakeven point that balances sustainability. All aspects of sustainability should be reconciled through a proper decision making process, while not completely compromising another.

3.2 Sustainability Assessment Methods

Traditional infrastructure development has primarily focused on maximizing economic performance due to budgetary constraints (Mirza 2006). Academia and industry have employed economic, environmental, and social assessment methods even prior to the formal inception of sustainability. Owners perform cost/benefit analyses to maximize return-on-investment and to confirm project feasibility. The National Environmental Policy Act (NEPA) in 1969 has required full consideration of impact to the natural and human environment (EPA 2012). An Environmental Impact Assessment (EIA) assesses possible positive and negative impacts related to the social, environmental, and economic impacts. An EIA is a good approach; however, a full scale EIA takes significant time and effort to complete. Subsequently, an EIA is not recommended for small scale underground infrastructure projects. There are several approaches to developing a practical assessment rating method for building and infrastructure construction projects. Leadership in Energy and Environmental Design (LEED) is the most successfully implemented rating system in building construction. The U.S. Green Building Council (USGBC) manages and certifies a level of grade as guided by the LEED system. Greenroads™ was specifically developed in 2010 for roadway projects. It is a rating system similar to the LEED system. The Institute of Sustainable Infrastructure (ISI) is an independent non-profit organization founded in 2011 by the American Society of Civil Engineers (ASCE), the American Council of Engineering Companies (ACED), and the American Public Works Association (APWA) (ISI 2012). ISI is currently developing an infrastructure sustainability rating system. At this present time, there is not a sustainability assessment method that is officially accepted in the underground infrastructure industry.

Koo et al. (2009) proposed the Sustainability Assessment Model (SAM) using the Analytic Hierarchy Process (AHP) for qualitative indicators and various estimation techniques for quantitative indicators. Sustainable construction methods can be evaluated and selected by multi-criteria decision making technique combining both qualitative and quantitative.

For years, studies and research about social cost quantification have been discussed to promote trenchless technologies over traditional open cut methods. Quantification of social costs can estimate indirectly related costs prior to making a construction method selection. Matthews and Allouche (2010) proposed a Social Cost Calculator (SSC) to estimate various social costs. The SSC includes: 1) traffic delays; 2) vehicle operating costs; 3) pedestrian delays; 4) parking losses; 5) noise pollution; 6) dirt pollution; 7) air pollution; and 8) pavement restoration costs. They used various cost factors from other references and developed a computer application to calculate overall social costs during the construction phase.

Emission estimation is an approach to assess environmental impact during a construction phase. Sihabuddin and Ariaratnam (2009), Ariaratnam and Sihabuddin (2009), and Piratla et al. (2012) developed an emission calculator using various emission factors as multipliers to estimate total emission during a construction phase. Their studies include: 1) embodied energy; 2) hydrocarbon; 3) carbon monoxide; 3) nitrogen oxides; 4) particulate matter; 5) carbon dioxide; and 6) sulfur oxides. Various construction methods can be quantitatively compared using the emission estimation. Compared to traditional open cut methods, trenchless technologies only produce a fraction of emissions mainly due to using less fossil fuel during the construction stage.

Most social impacts are intangible and qualitative in nature. Assessment for social impacts tends to be subjective and difficult to quantify. Therefore, multi-criteria decision making techniques including AHP are often used to assess social impacts. Examples of social impacts include: 1) public and social safety; 2) influence on local business; 3) social and cultural activity; and 4) historical and archeological value.

4. SUSTAINABLE TRENCHLESS SOLUTION FRAMEWORK

Selection of the most sustainable construction method should be made during design feasibility or value engineering phase prior to the actual engineering design process. Construction method selection should be made using several assumptions:

- A consensus among stakeholders has been made to meet public demands such as service area expansion and quality of life improvement. The owner is ready to approve the project and there is no extreme antagonism from social, political, and environmental activists group.
- The owner is able to secure project budget and rate payers are acceptable to paying an adjusted rate.
- Proposed preliminary design concept is viable and can be approved by the owner and regulatory agencies. The concept may include capacity, depth, alignment, route, etc.

Due to the nature of a typical construction project, development of an accurate direct construction cost index is a challenging task because every individual project is different. Until recently, engineers and utility owners considered trenchless technology to be expensive and not a viable alternative construction method. Success stories of trenchless projects have improved this misunderstanding and the overall acceptance rate has increased. Cost is still the single most critical factor in determining design and construction method selection. Cumulative trenchless construction bid data collected in 2002 and 2003 by Simicevic and Sterling (2003) is presented in Figure 2. The results from this data collection support the fact that several trenchless technology methods are more economical than conventional open cut methods. In addition, water rehabilitation cost data in 2003 and 2004 collected by the Office of Water Service in the United Kingdom confirms that renewal methods including epoxy lining, slip lining, pipe bursting methods were more economical than a conventional open cut method in urban environments (OFWAT 2005).

Table 1 is a summary of relative comparisons in terms of three verbal scales between conventional open cut and representative trenchless technology methods. Three scales (i.e. high, medium, and low) are determined for a typical urban underground infrastructure project. Relative comparison assessment is subject to refinement when applied to a specific real world project.

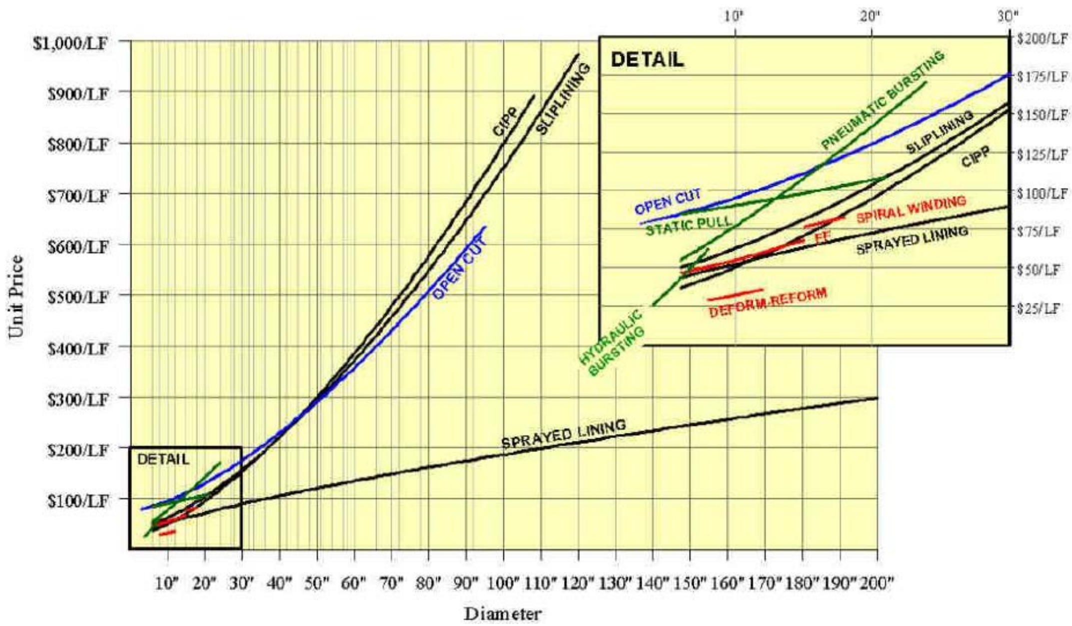

Figure 2. Installation cost in 2003 Dollars for Open Cut and Trenchless Rehabilitation Methods (Simicevic and Sterling (2003)

Table 1. Summary of Relative Comparisons in Three Scales

Assessment Criteria / Construction Method	Direct Const. Cost	Structural Level	On-line / Off-line	Const. Duration	Traffic Impact	Social Impact	Envir. Impact	Restor. Impact	Exist. Structure Impact
Open Cut	Medium	Full	Off-line	High	High	High	High	High	High
Sleeve Repair	Low	None	On-line	Low	Low	Low	Low	Low	Low
Joint Repair	Low	None	On-line	Low	Low	Low	Low	Low	Low
Cement Mortar Lining	Medium	None	On-line	Low	Low	Low	Low	Low	Low
Epoxy Lining	Medium	None	On-line	Low	Low	Low	Low	Low	Low
Polyurethane/Polyurea Lining	Medium	None/Semi	On-line	Low	Low	Low	Low	Low	Low
Cement/Polymeric Grouting	Medium	None	On-line	Low	Low	Low	Low	Low	Low
Close Fit Lining	Medium	Semi/Full	On-line	Low	Medium	Low	Low	Low	Low
Fold and Form Lining	Medium	Semi/Full	On-line	Low	Medium	Low	Low	Low	Low
CIPP	Medium	Semi/Full	On-line	Low	Medium	Low	Low	Low	Low
CIPP (non-styrene)	Medium	Semi/Full	On-line	Low	Medium	Low	Medium	Low	Low
Sectional CIPP Repair	Low	None/Semi	On-line	Low	Low	Low	Low	Low	Low
UV-CIPP	High	Full	On-line	Low	Medium	Low	Low	Low	Low
Sliplining	Medium	Full	On-line	Low	Medium	Low	Low	Low	Low
Spiral Wound Lining	High	Full	On-line	Medium	Medium	Low	Low	Low	Low
Pipe Bursting	Medium	Full	On-line	Medium	Medium	Low	Low	Low	Medium
Microtunneling/Pipe Jacking	High	Full	Off-line	High	Medium	Low	Low	Low	Low
Directional Drilling	Medium	Full	Off-line	Medium	Medium	Low	Low	Low	Low
Auger Boring (Pilot Boring)	Medium	Full	Off-line	Medium	Medium	Low	Low	Low	Low
Pipe Ramming	Low	Full	Off-line	Low	Low	Low	Low	Low	Medium
Pipe Piercing	Low	Full	Off-line	Low	Low	Low	Low	Low	Low

Structural level is categorized by non-structural, semi-structural, and fully structural. The open cut method directly installs a new pipe and thus is considered to be fully structural level. Several trenchless technologies are only available in either non-structural or semi-structural level option. On-line and off-line is determined by whether the method uses the existing pipeline or not. Most rehabilitation and replacement methods are considered to be on-line. Utilizing the existing pipeline provides tremendous benefits in effective and efficient underground space utilization. Future development will gain benefit by using available underground space. Temporary bypass service backup systems are required to maintain existing utility service while construction takes place. The bypass system is a major cost and schedule factor for any underground infrastructure project. Some trenchless technologies such as sliplining can be done without the need for a bypass system, while not compromising existing service. Many other aspects of sustainability are related to disruption level in construction jobsite caused during the construction phase. The total magnitude of impact is multiplied construction time by level of disruption. Thus, construction time is a key factor to determine sustainability of a construction method. The following aspects should be included, but not limited to, in the assessment framework.

- Traffic impact includes size of equipment footprint, area of traffic control, traffic control duration, additional vehicle maintenance and operation cost, additional gas consumption, and loss of workable hours and income due to traffic delays caused by the selected construction method.
- Social impact includes pedestrian delays and nuisance, public safety, jobsite safety, social activity impact, and local business impact caused by the selected construction method.
- Environmental impact includes emission, noise and dirt nuisance, water pollution, and embodied energy caused by the selected construction method.
- Restoration impact includes the level of restoration needs caused by the selected construction method.
- Existing structure impact includes early deterioration of existing structure caused by the selected construction method.

Figure 3 demonstrates a sustainable construction method selection framework using various assessment categories in Table 1. The framework focuses on decision making process for a specific type of underground infrastructure construction method selection. Application for other types of infrastructure development such as roadway or bridge can share the concept of Figure 3. However, technical design and condition should be updated as minimum modification. The framework does not intend to measure life cycle assessment (LCA) for environmental input and output and life cycle cost analysis (LCCA) because of many missing essential data to be used in an actual project decision making. LCA and LCCA are well established and can be separately performed. The results from LCA and LCCA can be used as an additional decision factors for a multi-criteria decision making (MCDM) process in Figure 3. On-line condition defines that the main function of an underground infrastructure system should be remained during project development. Off line is in opposite condition. Determination of This paper does not cover details of various MCDM techniques. Previous studies discuss various MCDM applications using AHP, fuzzy logic, and weighted factor.

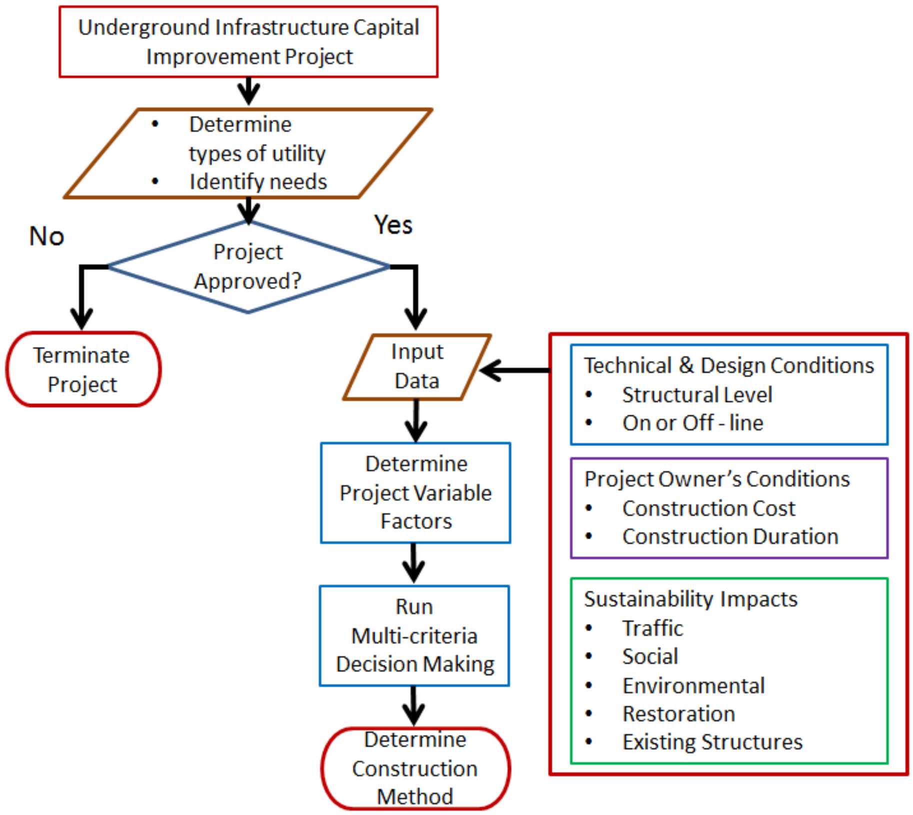

Figure 3. Example of Sustainable Construction Method Selection Framework

CONCLUSIONS

The paper summarizes a family of trenchless technologies and its sustainability impact aspects. Trenchless technologies have proven to be cost-effective, environmentally-friendly, and socially less disruptive as supported by many successful projects. The authors reviewed existing sustainability assessment methodologies and proposed approaches by others. The concept of sustainability is based on a triple bottom line including economic, environmental, and social aspects. The triple bottom line was reviewed by the authors and incorporated as components of a sustainability assessment framework proposed in this paper. An underground infrastructure project in an urban environment should be considered through a broad perspective view of sustainability because a project has tremendous economic, environmental, and social impacts.

The proposed classification tree can be used by the owners, engineers, and contractors who consider trenchless alternatives over conventional open trench methods. Trenchless technology has distinctive pros and cons, thus comprehensive knowledge and experience of a decision maker is essential to determine the most suitable technology. The framework is intended to be used by any project stakeholder that seeks a sustainable construction method and technology, particularly for urban underground infrastructure projects. Table 1 presents a series of relative comparisons between conventional open cut and typical trenchless technology. Actual field data can improve the effectiveness of sustainability assessment during selection framework application shown in Figure 3. The framework is developed to focus on a simple but practical approach. This framework can be useful to a decision maker to establish a systemically viable decision making process for their regular underground infrastructure capital improvement projects.

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