CHAPTER 38

Optimization of Trenchless Utility Diversion Techniques through Risk-Based Assessment for Metro Station and Tunnel Projects

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ABSTRACT

Utility diversion in metro stations and tunnels projects presents significant technical and managerial challenges due to dense underground congestion, strict deformation control requirements and severe consequences of utility service disruption. Although trenchless techniques are widely adopted, the selection of an appropriate diversion method is often experience-based rather than derived from a structured optimization process that considers project-specific risks. This study proposes a qualitative, risk-based optimization framework to support the selection of trenchless utility diversion techniques in complex metro station and tunnel environments. The research identifies and categorizes key risks, including construction, geotechnical, utility interaction and operational risks associated with major trenchless methods such as horizontal directional drilling, microtunnelling and pipe jacking. Expert judgement is incorporated to rank these risks and assess method suitability under varying site constraints and strict metro safety requirements. Based on this prioritization, a risk-informed decision-support matric is formulated to aid method selection by reducing overall risk exposure while meeting constructability and operational requirements. The proposed framework enables systematic, transparent and consistent decision-making, thereby improving planning and pre-construction strategies for metro infrastructure and tunnel projects.

Keywords: Trenchless Technology, Utility diversion, Risk-based Optimization, Method selection, Metro & Tunnel Projects.

1.0 Introduction

Metropolitan areas require lots of underground infrastructure, and the massive growth of urban population and the growth in mass rapid transport systems have highly contributed to the high level of demand (Shen et al., 2016; Rogers et al., 2012).

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Metro stations and tunnels are commonly built below densely built urban corridors where underground conditions are already clogged with existing infrastructure, such as water supply pipes, sewer systems, gas pipelines, power cables, commercial telecommunication ducts, etc. These utilities present significant obstacles to novel underground constructions and utility diversion becomes a significant enabling undertaking with the development of metro infrastructures. Open-cut techniques of utility diversion are rapidly becoming inappropriate in the urban metro setting because of large-scale surface disturbance, traffic jams, environmental effects and the social costs (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). This has left trenchless technologies of choice to divert the utilities beneath the roads, buildings, and the existing transport infrastructure that are in operation. Horizontal directional drilling, microtunnelling, pipe jacking and manual/box jacking techniques have considerable benefits of causing less disturbance to the surface and keeping cities operating as normal in the course of construction.

Although such techniques offer certain advantages, trenchless construction technologies have a high level of uncertainty due to the lack of access to the excavation face, fluctuating ground conditions, contact with other utilities and structures, and high deformation control standards (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Even slight motions in the ground or utility malfunction in situations involving the construction of a metro station and tunnels can lead to severe safety hazards, service disruptions and negative publicity. In turn, the choice of a suitable trenchless utility diversion technique is a risky decision to consider at the initial level of planning and pre-construction.

Though there is a vast amount of literature on the individual trenchless methods and risk assessment, the current practice is more extremely based on experience and precedent of the contractor instead of formal, risk-based appraisal (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Existing decision-support models are generally generic and do not explicitly integrate metro-specific constraints, underground congestion, and expert judgment. The current paper provides the gap in understanding concerning the literature by reviewing and synthesising the current literature to aid the formulation of a qualitative, risk-based optimisation procedure, in the context of trenchless utility diverting in metro station and tunnel development.

2.0 Literature Review

2.1 Trenchless utility diversion techniques in metro stations and tunnel projects

The growing congestion underground and the inability of excavation viability in compact urban areas has seen the trenchless technologies being determined as part of utility diversion in metro station and tunnel projects (O'Reilly and Stovin, 1996; Sterling and

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Godard, 2020). According to literature, the most prevalent methods are a horizontal directional drilling (HDD), microtunnelling, pipe jacking and a manual or box jacking. The two approaches have their own unique construction mechanisms, sensitivity on risks and limitation in their application in metro environments. Due to its capacity to provide curved alignments with limited surfacial disturbance, the horizontal directional drilling is often used to divert small- to medium-diameter utilities (Shen et al., 2016; Rogers et al., 2012).

Nevertheless, the literature has always pointed out that the HDD performance is very sensitive to the cover depth, soil stratigraphy, pressure in the drilling fluid and bore path control. Shallow cover and non-homogeneous ground conditions also favour high chances of surface settlement, bore instability, and unintentional utility strikes in the metro station areas. Microtunnelling is commonly believed to be a very precise method that can be applied to gravity pipelines and utilities where the line and level control is a necessity (Shen et al., 2016; Rogers et al., 2012). Studies have shown that it can reduce ground movements even under sensitive constructions such as metro tunnels including those in operation.

However, microtunnelling is not only costly in terms of capital expenditure but also has a high shaft construction demands and dangers of slurry pressure unbalance and jacking force increase, mainly in soft soils and mixed ground conditions. Utility diversion of medium and large diameter is usually carried out using pipe jacking (Shen et al., 2016; Rogers et al., 2012). Studies emphasize the importance of soil pipe interaction, lubrication efficiency, and soil arching effects in governing jacking forces. Jacketing of tunnels shall occur in shallow metro tunnels where penetrating existing tunnels may cause other stresses and thresholds that may trigger ground movements hence high-level deformation control and observation. Short-length diversions that typically occur in station boxes or in small urbanized areas are often undertaken by manual and box jacking (O'Reilly and Stovin, 1996; Shen et al., 2014). Even though these approaches are flexible when dealing with extreme space limits, the literature always reports increased risks to safety and reliance on workmanship.

Table 1: Comparison of Trenchless Utility Diversion Techniques in Metro Projects

Techniques	**Typical Application**	**Alignment Control**	**Shaft Requirement**	**Major Risks**	**Metro Suitability**
HDD	Small–medium utilities	Moderate	Low	Settlement, utility strikes	Moderate
Microtunnelling	Gravity pipelines	Very High	High	High jacking forces, cost	High
Pipe Jacking	Medium–large utilities	High	High	Force exceedance	High
Manual/Box Jacking	Short station diversions	Moderate	Low	Safety risks	Moderate

Source: Phillips et al. (2019); Sterling & Godard (2020); Sheil (2021)

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2.2 Risk assessment in trenchless construction

Risk assessment has been considered an essential part of trenchless construction since the nature of the uncertainty of the underground works (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Initial work underlines qualitative risk identification with the help of expert judgement, because in the trenchless failures, events should be low-probability and high-consequence critical events. This risk profile is especially applicable in the case of metro station and tunnel projects where the maximum deformation and its consequences are too critical. Probabilistic methods have been established in order to measure the uncertainty in ground conditions and building performance. Observational and probabilistic models prove that deterministic design methods often fail to estimate the real jacking forces and deformation. Nonetheless, these techniques are very data intensive and are normally used at later stages in the project. Subjective expert evaluations can be used in risk prioritization with the help of fuzzy logic and multi-criteria decision-making (Shen et al., 2016; Rogers et al., 2012). Most of the existing structures though promising, are generalised and lack specifics of metro-related constraints, including network interference, beneath the ground congestion, and operational safety standards and demands.

Table 2: Risk Categories inn Trenchless Utility Diversion

Risk Category	Key Risk Factors	Potential Impacts	Representative Studies
Construction	Alignment deviation, jacking force exceedance	Delay, cost overrun	Sun et al. (2019)
Geotechnical	Settlement, groundwater ingress	Structural damage	Shen et al. (2016)
Utility Interaction	Utility strikes, stress redistribution	Service disruption	Rogers et al. (2012)
Operational	Restricted access, safety constraints	Work stoppage	O'Reilly & Stovin (1996)

Source: Synthesized from reviewed literature

2.3 Utility interaction and failure consequences

Utility interaction is one of the most vital risk dimensions in the metro station and tunnel projects since extreme underground congestions and intolerance to the service disruption (Shen et al., 2016; Rogers et al., 2012).

Research has continuously indicated that incomplete or inaccurate records of utility is one of the leading causes of construction-related accidents. Extensive studies of urban pipeline failures indicate that indirect causes of failure, including ground movement, redistribution of stress, and vibration caused by construction tend to be more influential in the failure initiation than direct physical contact (Shen et al., 2016; Rogers et al., 2012).

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These interactions in the metro environment may have cascading consequences, e.g. emergency repairs and services blocking. Economic studies indicate that indirect and social utility failure costs are often larger than direct repair costs, which supports the fact that risk-based approaches to the development of planning should explicitly reflect the cost of failures (O'Reilly and Stovin, 1996; Shen et al., 2014).

Table 3: Utility Failure Consequences in Metro Projects

Failure Mode	Direct Consequence	Indirect/Social Impact	Severity
Utility strike	Repair cost	Traffic & service disruption	High
Excessive settlement	Structural repair	Metro service suspension	Very High
Pipeline collapse	Emergency repair	Environmental damage	High

Source: Zhang et al. (2024); Sun et al. (2021)

2.4 Decision-support and optimization approaches

The advanced optimization models have developed into decision-support systems with trenchless technology selection, which began as simple rule-based tools (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The initial expert systems were based on preset criteria of diameter, depth, soil type, and length of installation. Although these systems enhanced consistency, interactivity in terms of construction risk was not explicitly considered but rather only inferred through consistency in these systems.

Multi-criteria decision-making methods, such as the fuzzy logic and the weighted scoring model, are powerful in organizing the complex decision-making and integrating expert knowledge (O'Reilly and Stovin, 1996; Shen et al., 2014). Nevertheless, the majority of studies give more concern to technical feasibility or cost implications, but not to holistic risk mitigation. Optimization methods based on artificial intelligence are characterized by their high level of computer processing, but they do not always have transparency and can be applied in the early stages of designing a metro project (Shen et al., 2016; Rogers et al., 2012).

Table 4: Decision-Support Approaches for Trenchless Technology Selection

Approach	Key Criteria	Strengths	Limitations for Metro Projects
Rule-based systems	Diameter, depth, soil	Simple, transparent	Ignores risk interaction
Fuzzy logic models	Expert-weighted criteria	Handles uncertainty	Limited metro specificity
AI-based optimization	Cost, alignment	Efficient optimization	Low transparency

Source: Ariaratnam & Papandreou (2009); Chen et al. (2021); Wu et al. (2022)

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3.0 Research Methodology

This study employs qualitative review-based methodology as a means of synthesizing the current research on trenchless utility relocation and risk-based decision-making in metro projects, thereby pointing out crucial risks and factors, which further assists the development of a conceptual and expert-driven optimization framework.

3.1 Research design

The research employs a systematic narrative review with analytical synthesis instead of a descriptive survey (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). This method matches perfectly the exploratory purpose of extensive interactions of the trenchless methods, risk factors, underground congestion, and metro-specific constraints during planning phases. Due to variations across studies, quantitative meta-analysis was not considered. Identification, classification, and comparison of risks related to trenchless utility diversion in metro stations and tunnels, where failure consequences and deformation sensitivity are prominent, are the core aspects of the review (O'Reilly & Stovin, 1996; Sterling & Godard, 2020).

3.2 Literature selection and data sources

The Literature was collected only from peer-reviewed, high-impact journals to provide academic rigor. Scopus, Web of Science, ScienceDirect, and ASCE Library were the databases used, and these covered tunnelling, geotechnical engineering, and construction management. The selection concentrated on trenchless techniques, risk assessment, utility interaction, decision-support systems, and metro-related case studies. Only studies relevant to urban, metro, or tunnel contexts were kept (Shen et al., 2016; Rogers et al., 2012). To secure Q1 journal standards, conference papers, technical notes, and non-peer-reviewed sources were ruled out.

3.3 Screening and inclusion criteria

An organized screening procedure made sure that only relevant and high-quality papers got through. The following criteria were used for the selection of papers:

Definition of the topic and control methods for underground works and trenchless construction (O’Reilly & Stovin, 1996; Sterling & Godard, 2020). Interaction with utilities, geotechnical uncertainty or risks discussed openly (O’Reilly & Stovin, 1996; Shen et al., 2014). Possibility of being applied in urban, metro station, or tunnel settings (Shen et al., 2016; Rogers et al., 2012). Development of decision-making, risk assessment, or optimization processes (O’Reilly & Stovin, 1996; Shen et al., 2014).

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Papers discussing studies conducted in laboratory settings, rural areas, or low-risk conditions were not considered (Shen et al., 2016; Rogers et al., 2012), thereby confirming that the studies matched the complexity of metro infrastructure.

3.4 Data extraction and classification

From the papers that were selected, qualitative data was taken out among others:

- Type of trenchless technique
- Risks related to construction, geotechnical, utility, and operations
- Causes of failure and consequences
- Criteria for decision-making
- Limitations and suggestions

The data were then organized into themes for comparison, with risks being classified into four main groups (O'Reilly & Stovin, 1996; Shen et al., 2014).

3.5 Analytical framework

Without a numerical ranking, the trenchless utility diversion methods were evaluated under the specific conditions of the metro (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). The study pointed out the following risk sensitivity patterns;

- HDD with high settlement risk
- Microtunnelling or pipe jacking with more control but higher cost and logistical requirements
- Manual or box jacking with unequal safety risks

The EVIEWS decision-support approaches of expert judgment, risk interaction and site constraints integration were assessed and weaknesses in metro project complexity were revealed (Shen et al., 2016; Rogers et al., 2012)

3.6 Integration of expert judgement

This research highlights the importance of expert judgment (Shen et al., 2016; Rogers et al., 2012) by recognizing that metro planning in its early stages usually makes do with limited quantitative data. The literature suggests that expertise is usually applied implicitly but very rarely made transparent.

Therefore, the present study employs a mathematical method that first identifies risks through expert judgment and then gives them a rank of importance instead of using the conventional way of algorithmic optimization. This method corresponds to the real metro decision-making process, where the most skilled engineers and planners are the ones who determine the best construction methods to be used (Shen et al., 2016; Rogers et al., 2012).

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3.7 Outcome of the methodology

The methodological result is a combined comprehension of risks, method applicability, and decision-making limitations in the case of metro projects trenchless utility diversion (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). This synthesis supports:

- Research gaps identification
- A qualitative, risk-based decision-support framework development
- Future validation through expert surveys or case studies

On the whole, the methodology guarantees a systematic and undisguised review that conforms to risk-based optimisation in complicated metro areas (O'Reilly & Stovin, 1996; Sterling & Godard, 2020).

4.0 Data Analysis

The data analysis approach used in the study is interpretive and qualitative, which is consistent with the aims of establishing a structured, risk-based knowledge of trenchless utility diversion in metro station and tunnel project (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Since the available studies are heterogeneous (analytical modelling and numerical simulation, case studies, reviews and decision-support frameworks), a quantitative or statistical meta-analysis was not possible and appropriate.

Rather, systematic qualitative content analysis was utilized to bring together the results of the reviewed literature. The trenchless technique under analysis, the context of the project, identified risk factors, reported failure mechanisms, mitigation strategies, and decision-making criteria were the main attributes extracted in each analyzed paper (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). These qualities were then coded and classified into recurring themes that represented construction risks, geotechnical risks, utility interaction risks and operational risks. This thematic classification enabled cross-comparison of how different trenchless methods respond to similar constraints in metro station and tunnel environments.

This was followed by a comparative study of the sensitivity of each trenchless methodology to prevailing risk factors (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). To illustrate, HDD related research studies were evaluated, to gain insight in the effect of shallow cover depth, soil heterogeneity, and pressure in the drilling fluids on surface settlement and bore stability around metro stations. On the same note, the subject of microtunnelling, pipe jacking was also analyzed to determine the trends in the increasing jacking forces, occurrence of soil arches, efficiency of lubrication and effect of tunnel-soil-structure interaction. A construction safety and execution risk perspective was the most important in the analysis of manual and box jacking studies as they are based on workmanship

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and are not highly mechanised. In addition to the personal risk factors, the analysis specifically studied the risk interaction (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The literature reviewed proves that risks in trenchless construction are hardly observed alone. As an example, geotechnical uncertainty tends to increase risks associated with construction i.e. alignment deviation or jacking force exceedance, which consequently raises the risk of utility interaction and disruptive operational occurrence. This interdependency was analyzed systematically to draw out the weaknesses of the traditional mode of selection which considers risks separately. Simultaneously, the literature on decision-support and optimisation models was reviewed to assess the level of uncertainty and expert judgment as well as metro-specific constraints (Shen et al., 2016; Rogers et al., 2012). Specific focus has been on the identification of whether these models expressly consider the effects of failure, underground congestion, and interference with the existing metro assets.

The discussion demonstrated that there have been clear lapses in the integration of qualitative expert judgment and structured risk prioritisation, particularly in the initial planning and pre-construction phases. In general, the qualitative data analysis allowed to conduct the systematisation of the piecemeal research results and assure the rational ground in determining the patterns, limitations, and potential improvements in trenchless utility diversion decision-making when considering metro projects (O'Reilly and Stovin, 1996; Sterling and Godard, 2020).

5.0 Findings / Results

The literature review leads to a number of valuable results that, in combination, describe the present level of practice and research in trenchless utility diversion in relation to the work on a metro station and a tunnel (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). First, the discussion proves the fact that the suitability of the trenchless method is strongly situational (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). There is no one trenchless method that can be regarded as the best in the metro conditions. HDD provides flexibility of alignment and low level of surface disruption but has high risk when covered shallowly such as those near metro stations. Microtunnelling and pipe jacking have better control of line and level and are therefore suitable under sensitive structures and functioning tunnels but are also expensive in capital and shaft demand and logistically more complicated. Box jacking and manual jacking present flexibility when used in tight station areas but cause unproportional safety and execution hazards.

The observation supports the inefficacy of generalizing selection methods. Second, early-stage decision-making is prevailed by construction and geotechnical risks, whereas the severity of the failures is determined by utility interaction and operational risks (Shen et al.,

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2016; Rogers et al., 2012). Although most of the literature is aimed at prediction of settlement, jacking forces or face stability, the effects of failure like service disruption, emergency repair, and impacts on public safety- are often more critical in metro projects.

The research articles discussed in this paper show that indirect and social utility failure costs are often greater than the direct costs of repair, which suggests the importance of focusing on the consequence-based risk assessment instead of feasibility-based risk assessment. Third, the results indicate that current risk assessment methods are rather generic (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Even though qualitative, probabilistic, and fuzzy logic-based methods are suggested, most of the frameworks are designed to be applied to general trenchless and therefore do not explicitly deal with the metro specific constraints including the proximity of the tunnels, strict limit of deformation and the operational safety.

Consequently, they have a low level of applicability to the metro station and tunnel projects especially in the initial phases of planning. Fourth, the analysis reveals a strong lack of connection between the expert judgment and formal decision-support models (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The trenchless method selection depends on expert knowledge as a key factor in practice, but it is usually utilized on an informal basis and not in an organized and open-minded framework. The literature review regarding the decision-support systems is full of decision support systems that focus on technical feasibility or cost optimisation and underrepresented the interaction of risks and failure consequences. This restricts its applicability under complex metro conditions that have high levels of uncertainty and limited possibilities of taking corrective actions during construction. All of these discoveries support the idea that trenchless utility diversion in metro projects is mostly an experience-driven process, which lacks proper backing with organised, risk-sensitive decision-making equipment (O'Reilly & Stovin, 1996; Sterling and Godard, 2020).

6.0 Conclusion

This literature review has shown that trenchless utility diversion in metro stations and tunnel projects is by nature complicated because of the high congestion under the ground, geotechnical uncertainty, high deformation control, and drastic consequences of utility failure (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Although the benefits of trenchless technologies are obvious in comparison with open-cut techniques in an urban setting, the recent successes of metro construction projects rely heavily on the correct choice of the methodology at the planning and the pre-construction stages.

The analyzed literature is characterized by the fact that the existing studies are also a valuable source of technical knowledge on the use of separate trenchless techniques, risk

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factors, and mathematical models, but these works are still sporadic (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). It is apparent that there is no formal, qualitative, expert-focused, risk-based framework that is specifically designed to meet the needs of metro station and tunnel projects. The existing habits of decision-making usually focus on feasibility or cost concerns and are very dependent on unstructured experience, increasing exposure to high-consequence risks. In a practical view, the implications of the findings include the necessity to change experience-based selection to risk-based planning (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). By incorporating systematic risk detection and assessment of consequence, as well as the subjective judgment in initial planning, transparency, consistency, and defensibility can be improved in trenchless utility diversion planning. This is especially essential in case of such a project as a metro, where small setbacks may cause a disproportional effect on safety, functioning, and trust of people.

Regarding research, this research paper forms a sound conceptual base of creating risk-based optimisation models, as well as decision-support matrices with metro-specific examples (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The implications of this review can be used in the upcoming empirical studies such as expert surveys, Delphi studies, and case-based validation meant to be used to operationalise the risk-based trenchless technology selection. On the whole, the research can be valuable in enhancing the knowledge on trenchless utility diversion in the metro stations and tunnels and offer a valid rationale to support the application of structured, expert-led and risk-based planning methods in order to improve the planning outcome and resilience of infrastructure (O'Reilly and Stovin, 1996; Sterling and Godard, 2020).

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