Success is not final, failure is not fatal: it is the courage to continue that counts.

-Sir Winston Churchill

University of Alberta

Managing Tunnelling Construction Risks

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Construction Engineering and Management

Department of Civil and Environmental Engineering

Spring 2012
Edmonton, Alberta

ABSTRACT

Construction projects are often faced with complex challenges; all of which lead to difficult decisions and possibly disputes regarding liability of the parties. This research investigates the risks associated with tunnelling construction and uses the information to create a simplified risk register. The risk register may be used as a reference guide of responsible and proactive project planning that reflects industry standards, lessons learned and the currency of understanding of the owners and contractors. Additionally, a checklist was created to simplify risk assessment during each phase of construction by identifying possible hazards for each critical task of the project. By openly acknowledging and discussing risks in the contract, the author believes that the tone of the project will be set towards mutually beneficial progress and co-operation and the lessons learned on each project will also be easier to recreate and utilize on future projects.

ACKNOWLEDGEMENT

I dedicate this thesis to my family, without whom I would not have had the patience or support necessary to complete this research.

I would also like to thank my advisor, Dr. AbouRizk, for his encouragement and guidance through this research. Special thanks to my examining committee members Dr. Al-Hussein and Dr. Karapetrovic. Finally, I'd like to thank my friends for continued inspiration and the stress-relieving dinner parties, discussions and endless debates. Without you all this research would merely be a fragment of my imagination.

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INTRODUCTION

1.1 Problem Statement

Construction projects are often faced with complex challenges such as differing conditions, underestimated productivity, environmental or safety violations for example, all of which lead to difficult decisions and possibly disputes and litigation. The key to success on any construction project is to, therefore, have a competent and prepared team ready to mitigate as many risks as possible, as quickly as possible. Proactive construction companies even go as far as to include forecasting, analyzing and planning for risks that lie on the margin of or just outside the scope of the project. But even the most prepared construction team is still in harm's way if the forecasted risks are not accounted for and assigned to the stakeholders best suited to handle them.

Through a thorough literature search of current tunnelling practices this research aims to create an improved tunnelling construction checklist designed to account for hypothesized risks on the project's critical path. Furthermore, references are made to the relevance and importance of utilizing a risk register, public to all stakeholders of each project, which may accompany or be required in the construction contract. Loganathan (2008) suggested that contractors prepare and submit a preliminary geotechnical interpretative report (PGIR) in their construction bids to verify that the contractor understands the project, the requirements and the terrain and is competent to fulfill the duties. Similarly, this research’s checklist and risk register intend to verify understanding of the risks associated with tunnelling construction and expedite verification that the typical risks have in fact been accounted for, addressed and agreed upon by owners and contractors. The overall premise of this research is that if the risks are openly considered, addressed and assigned on each project they can be handled more efficiently.

This optimistic introduction intends to highlight the importance and usefulness of experience and lessons learned, combined with practical and theoretical knowledge and preparation. Tunnelling construction has modernized through trial and error and the author is suggesting that owners and contractors work together and share their lessons learned so as to increase the profitability of the project, by minimizing cost overruns and delays throughout the project but particularly on critical task and environmental violations.

It is also important to state that this research is merely the beginning of a much larger research project. All projects, regardless of similarities, are different and difficult. The checklist and risk register developed in this research are intended to serve as guidelines for tunnelling risk management; therefore, they are intended to be updated regularly as processes develop and adapted to suite different project conditions.

1.2 Research Objectives

The main purpose of this thesis is to assess the risks associated with tunnelling and incorporate best practices and prevention mechanisms into a checklist. The checklist aims to be a comprehensive document, based on a risk register, which draws attention to the common risks encountered on tunnelling construction projects, thus ensuring that they have been or are being considered and addressed. It is the goal of this research to produce a checklist that, when used in conjunction with the preferred risk management program, will ensure that both owners and contractors are actively involved in the risk management process.

Minimizing risks and disputes and potentially increasing profits are factors that are expected to be influenced by this research. It is expected that by acknowledging, anticipating and accepting the risks, construction companies and its associates will become more open about allocating construction risks.

1.3 Research Methodology

This research utilized a cycle that began with scientific curiosity into the risks involved with tunnelling construction. In this descriptive section of the research the author sought out facts about the current state of the tunnelling industry and its techniques. For this phase the author conducted a thorough literature search and recorded the findings, without having any preference or control over any variables encountered. The goal was to find patterns in the literature which would later be used for comparisons and validations.

Secondly, grounded theory, though not typically used for scientific research since it much resembles a reverse hypothesis, was used to generate a more precise research theory from qualitative data., This technique allowed the author to conduct analytical research of the risk analysis data from numerous projects in Edmonton, Alberta to pinpoint the actual needs of the industry based on observed patterns and gaps and. These observed patterns of the analytical research were used to create a theory which developed into the previously described scope around which this research project is based.

Finally, the author returned to a more conventional scientific research methodology of thoroughly researching the literature pertaining to the scope, followed by data collection, analysis and interpretation. This analysis section initialized the outputs of this research project which can be considered both fundamental and applied research. The fundamental research goal is “gathering knowledge for knowledge’s sake …” (Anderson and Anderson, 1951) while the applied research “aims at finding a solution for an immediate problem facing … an industrial/business organization” (Kothari, 2004). The final stage is to validate the theory and make conclusions and future research recommendations.

Subsequently, this research was conducted using a thorough literature search and analysis, a comparison of local tunnelling projects and a validation completed by interviews to review the applicability of the risk register by industry personnel. The literature search covered the following topics:

- Tunnelling processes and practices
- Tunnelling construction critical paths

- Risk management for tunnelling construction
- Risk registers

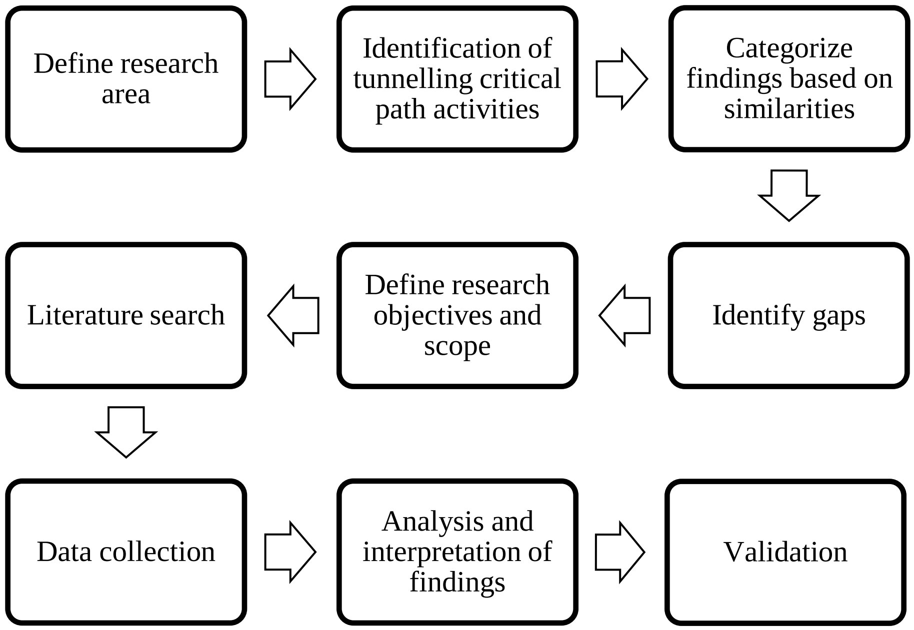

Figure 1: Graphical Representation of Research Methodology

Validation aims to ensure that the planning, execution, and evaluation phases of the research truly reflect the highest standard of quality of the industry. The validation of this research project was divided into three steps – content validity, criterion validity and face validity.

Content validity is achieved if the parameters of the research, such as tasks and environmental conditions, are accurate representations of those typical in industry. To achieve content validity of this research the author reviewed the actual schedules of four large tunnelling projects that have begun in Edmonton, Alberta within the past 3 years, the last of which is expected to finish January 2015, and extracted the lists of items on the critical path of each project. The partial project schedules and reports of six additional international projects were also reviewed and similar information pertaining to the critical path of each project was also recorded. The critical path activities of each project were mapped onto each other and the consistently overlapping tasks became the scope of this research. Each of the critical activities was thoroughly investigated and consensus among risks and mitigations were recorded in the risk register. Inconsistencies regarding risks and mitigation strategies were investigated further until consensus was reached and recorded in the risk register. The next step was criterion validity which Lucko and Rojas (2010) define as the ability of the results of this research to be successfully compared to that of similar research. Though there has been much work on the risk associated with tunnelling construction, the author found it particularly useful to compare this research to that of Flores (2006), who identified investigated and analyzed the state-of-the-art of tunnelling construction and created guidelines for managing risks from the viewpoint of the insurance industry, and the Institute of Risk Management's *The Joint Code of Practice for Risk Management of Tunnelling Works in the UK*. Finally, a case study was done of a 1500 meter long tunnel in a highway interchange project and the results were compared to those previously done by a consultant for the owner.

Face validity is the final step in this validity inspection and is the subjective judgment of non-statistical nature that seeks the opinion of non-researchers regarding the accuracy and quality of the study. This phase in the research process, therefore, required the inputs and collective approval of industry experts as to the study and its results being a true representation of reality. For this section of the validation the research area, objectives and outputs were discussed with five prominent members of the Albertan tunnelling industry at numerous intervals throughout the research. These discussions were based primarily on experiences and expectations as they related to the research being conducted. Each professional impacted this research by offering the author further insight into tunnelling construction and risk. Three of the five industry practitioners reviewed both the checklist and the risk register produced by this research and thought it very useful; the remaining two were unavailable during the final stage of the validation. Verification, according to Lucko and Rojas (2010), is "doing things right" while validation is "doing the right things". These are obviously two very important aspects of any research project, but since verification requires measurable performance parameters this research will not focus on physical practices that have already been established and deemed verified; instead the emphasis of this research is to validate the risk management techniques outlined in the following chapters to ensure that the planning, execution, and evaluation phases of the research truly reflect the highest standard of quality of the industry.

CHAPTER 2

BACKGROUND

2.1 Tunnelling Construction

Tunnelling is the process of excavating a long underground passageway. Over the years tunnelling has advanced from hand excavation to excavating with the latest high tech tunnelling machinery. Tunnels are classified into three categories with respect to their function – mining, public works, or transportation.

2.1.1 Types of Tunnels

<u>Mining tunnels</u>

The earth contains many precious metals and minerals that are valuable to mankind, but in order to have access to many of these elements, one has to go deep under the ground. The construction of mine tunnels was therefore necessary to provide easy access for ore extraction. Mine tunnels are not meant to be permanent structures. Due to this fact, they are significantly cheaper to build since they require less support after excavation. Mining tunnels are therefore also very unsafe as the risk for a collapse is much higher than other tunnels.

<u>Public works tunnels</u>

Modern life is only possible due to the many public works tunnels across the world. They contain utility pipe lines that service cities all over by carrying water, sewage, gas, electric and fiber optic cables amongst others, along vast distances.

These tunnels are usually smaller in size and do not provide the space necessary for human access. Public works tunnels are usually constructed using the tunnel jacking or pipe jacking method.

Transportation Tunnels

Transportation tunnels give vehicles and train systems the opportunity to travel underground in order to get to their destinations faster via direct routes. The first railway tunnels where built to run directly through mountains and hills as the railway system demanded railway tracks to be as flat as possible for the trains could only ride on tracks with moderate slopes. This in turn minimizes the time for travel between destinations making it an economical choice compared to taking a longer route in order to bypass mountainous areas. The same can be said for highway tunnels. The FHWA's *Highway & Rail Transit Tunnel Maintenance and Rehabilitation Manual* (2005) states that today's highways and underground mass transit systems are built in tunnels to prevent above ground transportation congestion in big cities. Transportation tunnels are usually the largest and most expensive tunnel projects. These tunnels can be constructed in a number of different shapes. The site ground conditions and the method of construction typically determines the shape of the tunnel.

2.1.2 Methods of Tunnelling

There are a number of methods that can be used for tunnel construction. The method used for tunnelling depends on several factors such as the type of rock or soil that is excavated, the location of the tunnel with respect to the surrounding environment, the construction budget, and the shape and size of the tunnel. The most common tunnelling methods are described below:

Immersed tube method

This method is used when tunnels are needed under a body of water. The shell of the tunnel is pre-made on dry land in sections. The most common materials used for the shell are reinforced concrete and steel. The underwater tunnel site is prepared by digging a trench big enough to accommodate the shell of the tunnel on the bed of the waterway. The pre-made sections are then sealed on either ends so that each section is able to float and be towed to the desired location above water. Once the section is in position, ballast tanks built into the section are flooded in order to sink the section to its final location in the trench, to be linked together to previous sections at the bottom of the waterway. The final step of this method is to backfill the trench with the appropriate soil.

The cut-and-cover method

This method uses the simple concept of excavating a trench, which is slightly larger in size than the shell of the tunnel, down to desired depth. The shell of the tunnel is then constructed usually with reinforced concrete. Once the shell is built, the trench is then backfilled and the ground above the tunnel is restored to its original state.

There are three ways of executing the cut-and-cover method (Mouratidis, 2008). The first is the bottom-up method; this method uses slurry walls or steel sheets driven into the ground at either side of the tunnel to prevent the soil from caving in once the excavation begins. Slurry walls are constructed by digging a narrow trench deep enough to reach just beyond the tunnel floor. While the trench is being excavated, a slurry mixture of clay is pumped into the trench to provide the pressure necessary to prevent the sides from caving in. Once the trench is at its desired depth, the slurry mixture is replaced with reinforced concrete to form a solid wall. Excavation can now begin between the walls to the bottom of the tunnel where a reinforced concrete slab is poured to form the floor of the tunnel. The roof of the tunnel is then casted from reinforced concrete with the support of the walls. The final step is to backfill the area above the roof to restore the ground to its original state.

The second method is the top-down method; this method is identical to the bottom-up method except for the fact that the roof is built first after the construction of the walls. Once the wall and the roof are in place, only then is the tunnel excavated down to the bottom where subsequently the floor is poured.

The third method is the cast-in-place method in which the trench is fully excavated to accommodate the entire shell of the tunnel at the desired depth. The walls of the trench must be protected with a shoring system of some sort to prevent the walls from caving in. After the trench is excavated, the forms to construct the shell of the tunnel are built inside of the trench. The concrete reinforcing is then placed inside the forms and the concrete is poured to form the shell of the tunnel. The final process is to backfill the trench to restore the ground to its original state.

Drill and blast (D&B) method

The drill and blast method was the predominant method to dig through hard rock before the invention of the Tunnel Boring Machine (TBM). This method uses a job specific drill called a “drilling jumbo.” Lees (2007), for the *Australasian Tunnelling Society* (ATS), published that this machine is able to drill more than just one hole into the rock at the same time depending on how many booms are attached to it. Once the drilling jumbo drills the correct pattern of holes into the rock, the holes are then carefully filled with explosives and detonated with a specific timing to make sure the blast does not affect any surrounding rock that must be left in place. The pile of rock left after the blast is then hauled away while workers use hand excavation to smooth out the newly blasted section and remove any loose rocks that did not fall by itself. Lastly, the new blasted section must be reinforced to prevent collapse. This is usually done by spraying a special type of concrete that adheres to the rock and gives support to the new section of the tunnel. This process is then repeated to continue with the development of the tunnel. The TBM has replaced much of this method, however, the drill and blast method continues to be used to this day for smaller tunnels where it is much more economical than the TBM.

Tunnel jacking (or pipe jacking) method

This method is primarily used to install underground piping for the purpose of utilities. Occasionally it is also used as an effective tunnelling method where minimal disturbance to the above ground is essential. The tunnel jacking method was used on the “Big Dig” in Boston which was one of the biggest tunnelling projects ever attempted (Salvucci, 2003). This method uses powerful hydraulic jacks to push large pipes or box shaped structures horizontally into the ground several feet at a time, while the inside of the structure is simultaneously being excavated. In the case of large tunnels, the box shaped structures are usually made of strong reinforced concrete. The first step to this method is to dig a pit big enough to build the entire section of the concrete box at the final depth of the tunnel, along with enough space to accommodate the jacking equipment. The concrete box is open at either ends. After the concrete structure is complete, it is then pushed horizontally a short distance by the jacks. The part of the concrete box that sliced through the soil is then excavated from the inside and the soil is then hauled away from the other end of the tunnel. This process is repeated until the entire concrete box is jacked into position. The roof of the concrete box act as a shield for the workers who are excavating on the inside to make sure there is no danger of collapse from above. When the concrete box is jacked all the way in position, it becomes a permanent part of the tunnel lining.

Tunnel Boring Machine method

This method uses a TBM that cuts a circular cross section into soil or rock to create a tunnel. The types of cutting edges used to bore through a tunnel are customized depending on the type of soil or rock being excavated. The TBM is therefore very versatile as it can bore through anything from solid rock to soft sand. The most advanced TBM’s can build the tunnel lining with precast concrete section at the same time it is boring the tunnel. At the face of the machine is a cutting wheel that slowly rotates to excavate the existing material. The cutting wheel also allows for the excavated material to be collected and hauled away through the machine with conveyor belt or other methods. The TBM is continually moving forward in order for the cutting wheel at the face of the machine to be consistently grind away at the soil or rock needed to be excavated. The built in jacks push against the most recently installed concrete lining of the tunnel to keep the TBM moving forward. In large tunnelling projects where the TBM's dig towards each other from either ends of the tunnel, it can be too expensive to demobilize the entire machine back out from the tunnel. In this case, the TBM's are usually left inside a short spur of the tunnel where they are permanently sealed away.

2.1.3 Future of Tunnelling Construction

With the development of new innovative tunnel construction methods and the advancement of tunnelling equipment, engineers will be able to construct larger, more cost effective tunnels in the future. Tunnel planning will dramatically improve with the help of the recently developed imaging technology that is able to scan the earth through sound waves in order to accurately determine the tunnel path, eliminating the need to disturb the ground before the actual construction of the tunnel. This tool is also able to determine the type of soil, rock, and potential geological irregularities on the path of the tunnel. The latest preferred method of constructing large tunnels is with the Tunnel Boring Machine (TBM). TBM improvements are underway to have it excavate and haul away the excavated material at a faster pace. This can be accomplished by having TBM's with multiple heads which can excavate two or more parallel tunnels at the same time. Engineers are also performing research on improving the cutting tools to make them last longer and more efficient as well as developing new stronger types of concrete with precisely controlled hardening rates. New excavation methods being experimented on to improve excavation through solid material are high-pressure water jets, lasers, and ultrasonic. Safety has always been a big issue with tunnel construction. Developments are on the way to make tunnel excavation machines even more automated to reduce amount of time people will have to be in the tunnel during excavation, hence improving the safety of tunnel construction (Wagner, 2007).

2.1.4 Challenges of Tunnel Construction

The biggest challenge in tunnelling is overcoming the uncertain ground conditions that lie in the path of a proposed tunnel. The International Tunnelling Association (2010) claims that geotechnical predictions that are as accurate as possible are vital to the success of a tunnelling project, since the geology is what usually determines the cost, the design, and the construction method of a proposed tunnel. Excavating in soft and highly variable soil conditions can lead to tunnel collapses that might delay a project or claim the lives of construction workers. An entire tunnelling project can be threatened if during excavation it turns out that the soil or rock is not as predicted as the tunnel might need a different construction approach all together which can cause the cost of a tunnel to go over budget.

2.2 Construction Risk Management

The Institute of Risk Management (IRM) defines risk as “the combination of the probability of an event and its consequences”. Similarly, risk management is defined as the methodical identification and treatment of risks, with the goal of sustaining benefits. Simply put, risk management aims to decrease the negative impact of risk and increase the positive impacts to create opportunity. To fully sustain benefits risk management is a continuous process. Mubin and Mubin (2008), Eskesen et al. (2004), and the *International Tunnelling Insurance Group* (2006) all recommend that the effective risks management can only be achieved if risks are assessed, analyzed and mitigated throughout each phase of a project and associated lessons learned should be integrated into the phases of other projects.

The IRM *Risk Management Standard* (2002) begins with the following statement about risk management:

> *It must translate the strategy into tactical and operational objectives, assigning responsibility throughout the organisation with each manager and employee responsible for the management of risk as part of their job description. It supports accountability, performance measurement and reward, thus promoting operational efficiency at all levels.*

The scope of all construction projects includes the assessment of risks for the health and safety of the workers and third parties (such as the public). Risk assessment is also done for damage to the environment, as well as neighboring properties, buildings, structures and infrastructure. Beyond the direct ramifications to the aforementioned, the scope of the project must also consider the financial loss, additional costs and delayed schedule as another layer of risks to the owner and contractor. Qualitative assessments are conducted to identify and raise awareness of the potential hazards of construction activities of the project. In this section of the project hazards are identified and classified and mitigation techniques are developed. Qualitative research can be conducted through brainstorming sessions with experts, industry literature or case files, or simply by reviewing the lessons learned from previous projects within the company. In this stage every aspect of the project should be considered and no potential hazards should be overlooked.

Though other risks occur in and affect construction projects, this research focuses only on the risks that occur during construction processes. These risks include:

- Technical risk
- Safety and operational risk
- Environmental risk
- Financial risk

Typically risks are time consuming and time sensitive. In construction every minute is directly related to a budgeted cost. Therefore, even the smallest risk at an inopportune time can derail an entire project with cost overrun. Accordingly, construction risk management requires that risks are maintained at “as low as reasonably practicable" (ALARP) levels and that mitigation measures are in place at all times and that the plan is diverse enough to work as a risk catch-all.

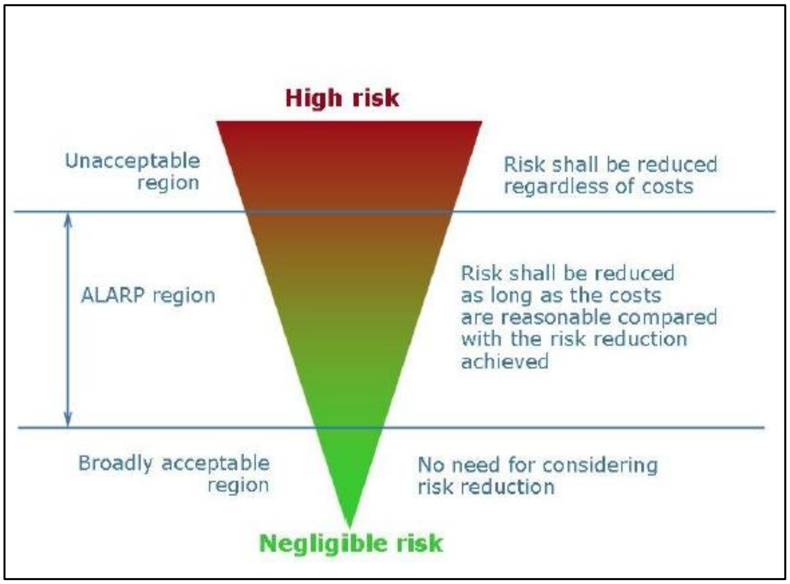

Figure 2: ALARP Principle (Eskesen, 2009)

2.2.1 Risk Management Process

A typical risk management process is divided into four evaluation phases:

- Risk Identification;
- Risk Analysis;
- Risk Mitigation; and
- Risk Monitoring and Control.

<u>Risk Identification</u>

Risk identification consists of reviewing the project and finding areas or events that might cause a problem or create a hazard. This is the "what could go wrong" phase, typically in review of the project's milestones. Countless techniques are available for the identification of risks, including brainstorming sessions, workshops, hazard and operability method (HAZOP), or checklists.

Risk Analysis

In this phase the potential problems and hazards from the risk identification phase are processed to determine a quantifiable level of danger posed to the project. Typically, either through experience-based or theoretical techniques, potential risks are classified. Analysis begins with the determining the cause, impact and likelihood of occurrence of the hazard.

As a true catch-all plan is unrealistic and unattainable because premise of a risk is that it is merely a possibility. Though knowledge of the possibilities may exist it is financially unfeasible to plan for or even analyze all potential risks. For that reason it is an industry-wide accepted practice to assess risks by assigning numerical factors to represent the likelihood of occurrence and corresponding impact of potential hazards. Though not an exact science, the result of such a comparison creates a risk severity matrix that can then be classified to represent confidence levels and tolerance. Though many methods exist, AbouRizk's (2009) depiction of common versions of a risk severity matrix and a risk tolerance matrix is shown in Figure 3 and 4 below.

		Disastrous	Severe	Substantial	Moderate	Marginal	Negligible
		1000	100	50	10	5	1
Very Likely	100	100000	10000	5000	1000	500	100
Likely	50	50000	5000	2500	500	250	50
Somewhat Likely	25	25000	2500	1250	250	125	25
Unlikely	10	10000	1000	500	100	50	10
Very Unlikely	3	3000	300	150	30	15	3
Extremely Unlikely	1	1000	100	50	10	5	1

Figure 3 : Risk Severity Matrix (AbouRizk, 2009)

Risk severity is calculated by multiplying the numerical factor assigned for probability of occurrence by the number assigned for impact. This example assigns probability factors ranging from 1 for Extremely Unlikely to 100 for Very likely while impact factors range from 1 for Negligible to 1000 for Disastrous.

		Disastrous	Severe	Substantial	Moderate	Marginal	Negligible
		1000	100	50	10	5	1
Very Likely	100	100000	10000	5000	1000	500	100
Likely	50	50000	5000	2500	500	250	50
Somewhat Likely	25	25000	2500	1250	250	125	25
Unlikely	10	10000	1000	500	100	50	10
Very Unlikely	3	3000	300	150	30	15	3
Extremely Unlikely	1	1000	100	50	10	5	1

Figure 4: Risk Tolerance Matrix (AbouRizk, 2009)

In the risk tolerance matrix above, owners and contractors may decide to include the mitigation costs only for risks with severities factors over 2000 as a project cost. This method of cost management is useful when consideration is given to the fact that it is extremely improbable that all possible risks for a project will occur; or even that all of the risks deemed severe or disastrous will occur. Accordingly, stakeholders typically determine an equation to deduce the amount of funds to be assigned to mitigating risks. This deduction is based on past experience, lessons learned and confidence levels.

Risk Mitigation

Once risks have been identified and classified as severe a plan of action against those risks must be implemented. Risk mitigation has four categories:

- Risk Reduction
- Risk Sharing
- Risk Retention
- Risk Avoidance

Risk reduction refers to minimizing the severity of the risks either by reducing its impact or probability of occurrence. This can be achieved through gaining more information on the hazard and realizing techniques to diminish the effects of the risk or by passing the risk on to the party best suited to handle it. Risk sharing involves enlisting another party to share the loss (or gain, if an opportunity arises) of the risks. Risk retention refers to absorbing the severity of the risk in whole, without trying to minimize or avoid it and accepting the implications of the risk on the budget. Risk avoidance is eluding the risks at all costs by not becoming involved. Though desirable for some scenarios, risk avoidance also avoids the possibility of gain or opportunity from overcoming a risk.

Risk Monitoring and Control

Risk monitoring and control is the management step in which ensures that strategies are put into action and their effectiveness and the lessons learned are recorded. In the event that a risk mitigation plan fails, this stage allows for contingencies and backup plans to materialize. Accordingly, new risks and residual risks are identified, restarting the risk management cycle and updating or changing the project's status.

2.2.2 Construction Risk Management

The types of risks and risk management previously mentioned in this chapter are not new. Nevertheless, owners and contractors are typically only concerned with the risks that directly affect their interests. Project partnerships and alliances have made significant strides towards emphasizing mutual benefit, but unless expressly statement in a contract, and even sometimes so, project participants remain adversarial. However, managing risks is the responsibility of all the project parties to the contract and success, whether individual or collective, is dependent on collaboration. A mutual risk management plan, presented through an easily-assessable risk register and checklist, is a useful method of identifying, analyzing, monitoring and controlling risks.

A risk register is the master list of probabilities from a risk management plan. It identifies a detailed description of the risk factors, the probability of occurrence, the risks' impact on the schedule, project scope, cost and quality of the project, parties responsible for each risk, and coordinating mitigation strategies. The risk register is not a fixed document and is instead intended to be a record of lessons learned on this project as well as from previous projects of either the owner or the contractor. Since the risk register is to be updated any time that a risk factor changes or more information about the risk is uncovered, it itself becomes a risk if the contained information is not up-to-date, clear and accurate.

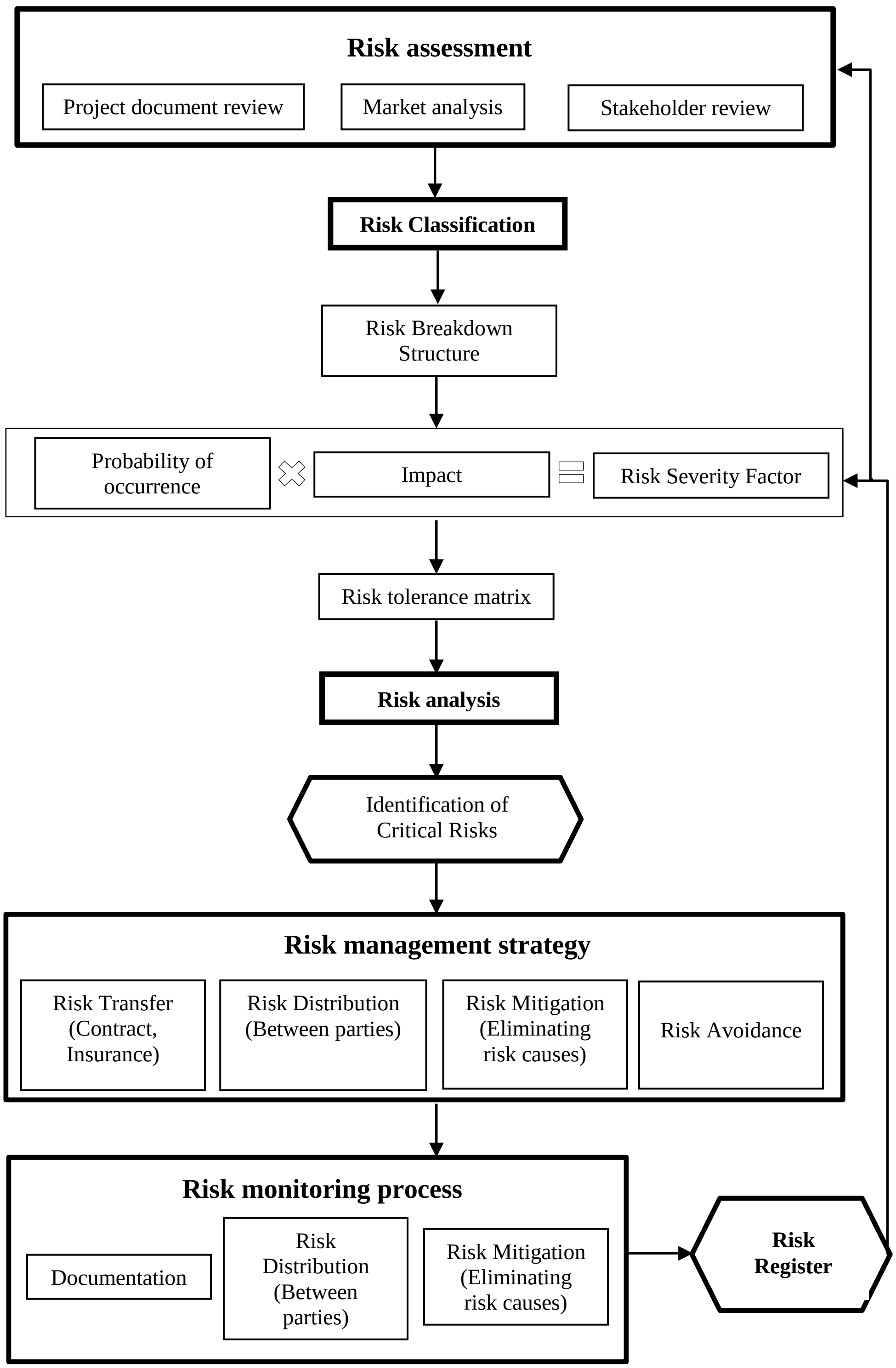

Figure 5: Risk Management Model (Adapted from Mubin and Mubin, 2008)

AbouRizk (2009), Eskesen (2009) and Mills (2001) are great sources for more detailed information on risks and risk management.

2.3 Risk Register

Though logical, quantifying risks can often be extremely difficult. Regardless of the efforts it is vital to the success of any project that the risks be identified and understood, and that a method is implemented to ease the harm caused by risks that materialize. There are numerous techniques for identifying, analyzing and mitigating risks. AbouRizk (2008) discusses the benefits of using standard checklists, expert interviews, the Delphi Technique and the Hazard and Operability (HAZOP); Akintoye and MacLeod (1997) explores research surveys; Eskesen et al. (2004) discuss the usefulness of fault, event and decision trees analyses; Kindinger and Darby (2000) use the Risk Factor Analysis (RFA) technique for early detection and quantitative risk analysis; while NASA (Stamatelatos, 2004) utilizes and continues to support the Continuous Risk Analysis methodology. Each risk mitigation strategy has its specific advantages and strengths, and determining which tool is best suited is usually defined by preference or application needs. The author and the authors previously referenced agree that regardless of the tool chosen to analyze and mitigate risks, the use of a risk register to record each risk and lessons learned is beneficial to all.

A risk register is a record of high-priority risks on a project in a database so that potential problems can be easily identified and that appropriate mitigation strategies are available for timely implementation. It openly documents all known information about the possible hazards associated with the project ensuring that no risks are taken unnecessarily or overlooked. The risk register must be a living document that is accessible and continuously updated by all stakeholders to reflect changes, advances and lessons learned. It will serve as a comprehensive document including details on the key risks that may be experienced on the project and potential mitigation strategies for each risk. This register can also be useful for minimizing insurance and bonds costs.

AbouRizk (2009) notes that the risk register can also be particularly useful to stakeholders; they may need the risk management information for future project planning. Williams (1994) goes further into the usefulness of the risk register and describes it as a complete risk management tool with a central role that “assists in time, cost and technical analyses, helps in the devising of a risk-management plan, and prompts decisions on risk transfer.” Williams continues by pointing out that in today’s industry where numerous companies work together on a single project a risk register becomes a valuable asset for sharing knowledge and for bridging the gap, in which major problems develop, between the different sections each party is assigned. Another advantage of a risk register that Williams points out is its ability to work as an audit trail, enabling decisions, assumptions and judgments to be traced back to their primary source.

Sections of a Risk Register

Each user may develop a personalized version of a risk register depending on the details that are specific to the company's needs; however, the typical design consists of the following information:

1. Basic Risk Information
    a. **Risk ID number.** A unique number that may be referenced to identify each risk.
    b. **Risk type.** Classification of the area of the project to which the risk refers. For example, Procurement, Mobilization, Excavation.
    c. **Risk description.** A clear and concise summary of the risk.
    d. **Risk reporter.** The name of the person reporting the risk.
    e. **Date reported.**
    f. **Date updated** if applicable.
2. Risk Assessment Information
    a. **Impact rating.** An assessment of the effect of the risk.
    b. **Impact description.** A clear and concise summary of the (possible) impacts of the risk.
    c. **Likelihood of occurrence rating.** An assessment of the probability of the risk occurring: Low (L), Medium (M), and High (H).
    d. **Severity of risk.** A measure of the magnitude of the risk, based on multiplying the impact and likelihood.

3. Cost Impacts

    a. **Minimum costs.** Lowest possible costs associated with the risk.

    b. **Most likely costs.** Expected costs associated with the risk.

    c. **Maximum cost.** Highest possible costs associated with the risk.

4. Schedule Impacts

    a. **Minimum time.**

    b. **Most likely time.**

    c. **Maximum time.**

5. Risk Response Information

    a. **Completed plan of action.**

    b. **Planned Future Actions.**

    c. **Risk Status.** An update indicating whether or not the risk was successfully dealt with, or at what stage it is in the process - current (C), ended (E), etc.

6. Comments

    a. Actual cost and duration

    b. Additional information pertinent to risk

The following risk register template (Figure 6 below) was created using a slew of risk principles and practices in order to provide a user-friendly, task-oriented model that can be accessed, utilized and updated by all stakeholders.

	1. BASIC RISK INFORMATION					2. RISK ASSESSMENT INFORMATION			
Risk ID	**Risk Type**	**Risk Description / Risk Event Statement**	**Reporting Party**	**Date Reported** day-month-year	**Date Update** day-month-year	**Impact** L / M / H	**Impact Description**	**Likelihood of Occurrence** L / M / H	**Severity of Risk**
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									

3. COST IMPACTS			4. SCHEDULE IMPACTS			5. RISK RESPONSE INFORMATION			
Min. Cost ($)	**Most Likely Cost ($) (Overall)**	**Max. Cost ($)**	**Min. Time (wks)**	**Most Likely Time (wks)**	**Max. Time (wks)**	**Completed Actions**	**Planned Future Actions**	**Risk Status** Open / Closed / Moved to Issue	**Comments**

Figure 6: Risk Register Template

As previously emphasized, the risk register is a comprehensive summary of lessons learned. It exists primarily on the premise of creating, updating and maintaining a thorough record of information pertaining to the risks associated with any given project.

2.4 Tunnelling Construction Risks

International Tunnelling and Underground Space Association (ITA-AITES), as one of the world's leaders in tunnelling initiatives, boasts a gathering of 64 member nations and over 310 corporate or individual affiliate members. ITA-AITES publishes internationally recognized guidelines and techniques for tunnelling risk management. In 2006, the International Tunnelling Insurance Group (ITIG) published *A Code of Practice for Risk Management of Tunnel Works* "to promote and secure best practice for the minimization and management of risk associated with … tunnels, caverns, shafts and associated underground structures…" Similar to the initiatives of ITA-AITES and ITIG this research aims to simplify risk mitigation availability amongst owners and contractors by documenting industry best-practices, theoretical advancements and knowledge gained from practical tunnelling experience.

As complete risks avoidance is impossible, especially when consideration is given to the uncertainty and unforeseeable nature of tunnelling construction, risk management can only aim to reduce risk to a level "as low as reasonably practicable" (ALARP). Accordingly, planning and strategizing mitigation techniques is crucial to successful tunnelling risk management. In a growing society tunnelling projects frequently arise with little time for extensive planning. Eskesen et al. (2004) state the following as common tunnelling construction risks that constantly require mitigation strategies and attention:

1. Risk to the health and safety of workers, including personal injury and, in the extreme, loss of life.
2. Risk to the health and safety of third parties.
3. Risk to third party property, specifically existing buildings and structures, cultural heritage buildings and above and below ground infrastructure.
4. Risk to the environment including possible land, water or air pollution and damage to flora and fauna.
5. Risk to the owner in the form of project delays.
6. Risk to the owner in terms of financial losses and additional unplanned costs.

Tunnelling Risk Management

Risks associated with tunnelling construction fall into four categories – (1) technical; (2) safety and operational; (3) environmental; and (4) financial risks. As previously mentioned every minute of a construction project is associated with a cost; therefore, the author chooses to focus primarily on the first three risk categories since they each add up to a financial risk. It should be noted, however, socio-economic, political and organizational factors also contribute to financial risks.

Critical Path Tasks for Tunnelling

Tunnelling construction, like most other construction disciplines, uses the critical path methodology for scheduling and managing projects. The critical path method (CPM) is a tool that is used to plan, coordinate and schedule projects and is typically used in conjunction with a work breakdown structure (WBS). The WBS details the activities and components of a project, to which the CPM can then adjust to show durations and relationships of the activities. The CPM utilizes interdependence details of all the tasks involved in the project from the WBS and calculates the minimum and maximum possible completion time without extending the duration of the project. Critical activities are therefore the tasks on the longest path as they represent the activities that must be completed within their specific allotted time if the overall project is to be completed on schedule. This process is so efficient that the *Project Management Institute* (PMI) states that the critical path method is the most widely used method of scheduling construction projects.

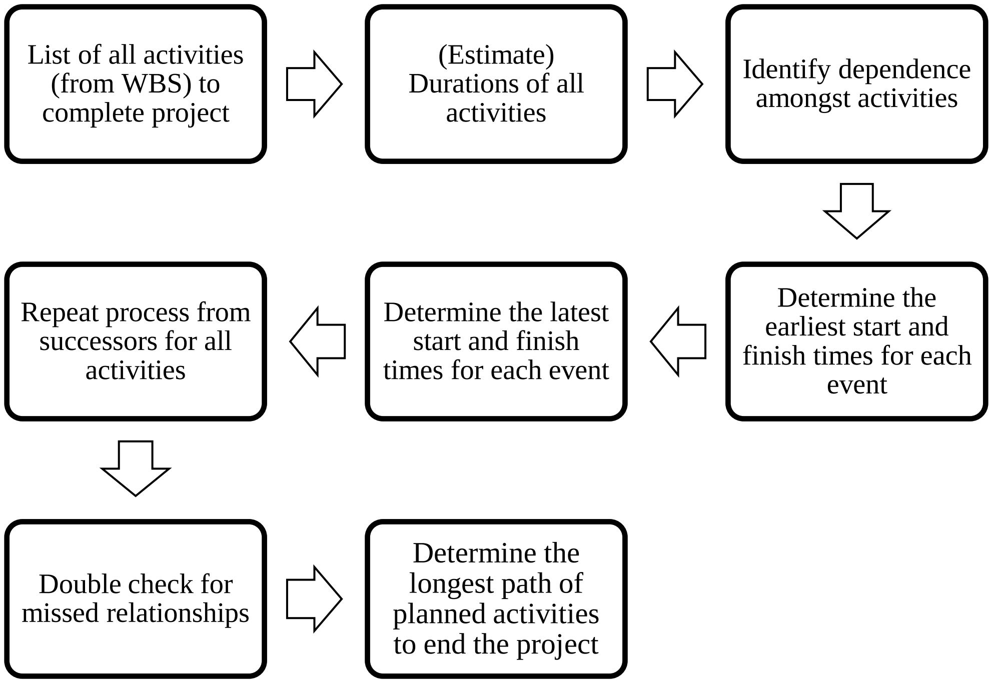

Figure 7: CPM Methodology (Adapted from Prensa, 2002)

Delays on a critical path will adversely affect the project's ability to be completed on schedule. Santiago and Magallon (2009) also emphasize that it is possible that a project may have several critical paths running parallel to each other, and some networks may exist with a typical long duration but also a shorter duration critical path which is called sub-critical or non-critical path.

However, tunnelling construction, when examined generally, is a linear process so most of the tasks are considered critical. Messinella (2010) stated that there are three primary processes in tunnelling construction – excavation, dirt removal and tunnel structural support. To identify the other tasks deemed critical in tunnelling construction, the author carefully reviewed four currently progressing tunnelling projects, utilizing tunnel boring machines (TBMs) in Edmonton, Alberta. The critical paths of these four projects and the partial project schedules and reports of six additional international projects were also reviewed and similar information pertaining to the critical path of each project was also recorded and became the scope of this research. The following activities were consistently on the critical path:

- Mobilization - Site prep and setup
- Excavation of the access shaft
- Excavation of the tail tunnel and undercut
- TBM installation
- TBM testing
- Tunnel (working shaft) excavation
- Dirt removal and disposal
- TBM removal
- Demobilization – site cleanup

The tunnel excavation or working shaft excavation is a good example showing the linear nature of the individual tasks associated with tunnelling. These are shown in Table 1 and Figure 8.

Table 1: Precedence Relationships between Tunnelling Utility InstallationTasks

Activity		Precedence
A	Lower TBM	---
B	Install TBM & Setup	A
C	Pour mud slabs & install switches	---
D	Excavate by TBM	B
E	Dismantle & Remove TBM	D
F	Clean up	E
G	Set up forms for cast-in-place concrete	F

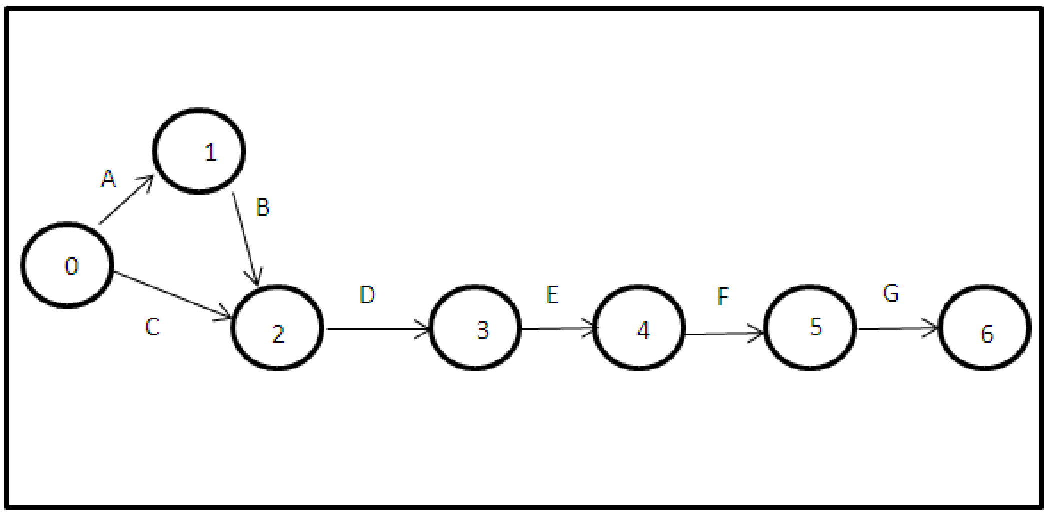

Figure 8: CPM Representation of Tunnelling from Working Shaft

The critical path of is depicted by the longest path once durations are added to the tasks *A* through *I* in Figure 8. Once an activity is deemed critical, it is extremely important to assess its productivity and also factors that may negatively affect its productivity. An adaptation of Messinella’s (2010) examination of expert opinions on tunnelling construction productivity factors is tabulated below.

Table 2: Productivity Factors for Tunnelling Construction (Messinella, 2010)

Productivity factor	**Description**
Operator's experience	Learning curve: years of experience, technical know-how of personnel
Soil / geologic conditions	Type, plasticity and moisture content
Job and management conditions	E.g. good communication lines, organized back-up system, availability of resources, skilled labour, etc.
Site conditions	Accessibility of site (urban or remote area)
Tunnel alignment	Shape of tunnel
Machine conditions	Amount of meters excavated
Shift type	Dayshift versus nightshift

Each task on the critical path of these four projects can be broken down further to reveal smaller tasks that contribute significantly to the criticality of the overlying tasks. However, other tasks are known to be critical though they do not always get listed as a heading on the critical path. Such activities include:

- Utility Location and Staking
- Shoring
- Backfilling
- Reclamation and Restoration

Other typical critical path activities, though not included as critical in all four of the projects reviewed will still need to be included to demonstrate comprehensibility. These activities are:

- Pipe installation and/or removal
- Gates installation
- Building/installing manholes

To simplify the analysis, the critical activities are grouped according to technical similarities. For example, *Excavation of the access shaft*, *Excavation of the tail tunnel and undercut*, *Shoring*, *Backfilling*, *Utility location and staking*, *Tunnel excavation* and *Dirt removal and disposal* are all directly related to each other and can be described and explained accordingly. The resulting classification of the critical tasks risks of tunnelling construction are categorized as follows:

1. Mobilization and demobilization risks
2. Excavation, backfilling and dirt removal risks
3. Equipment risks
4. Pipes, manholes and gates installation and removal risks.

CHAPTER 3

TUNNELLING CRITICAL PATH ANALYSIS

3.1 Mobilization and Demobilization Risks

Mobilization is the assembly, placement and setup of crews and equipment in preparation for the beginning of project tasks. As defined, the risks associated with mobilization involve acquiring crews and equipment, site layout and the placement and setup of crews and equipment. Demobilization, contrary to mobilization, is the removal of crews and equipment, and site cleanup after construction tasks have been completed. Most of the risks associated with mobilization are also accurate for demobilization.

One of the largest site mobilization or demobilization risks is a landslide (Tokmechi, 2011) or unstable ground conditions. A landslide is the sudden, unpredictable movement of earth and rocks down a steep incline. The risk of a landslide results from ground instability due to the effects of either a mechanized disturbance, such as excavation, vibrations or even heavy traffic, or from soil weakened from environmental sources, such as a heavy rainfall or soil erosion. Ground instability jeopardizes all aspects of mobilization and site preparation by possibly altering the choice of equipment and the site layout for the project.

The International Labour Office (1995) and Li et al. (2000) show that overcrowding and the poor placement of equipment and crews have proved to decrease productivity and workplace safety and an increase in the cost of rework.

Construction sites should be laid out with respect to the size of the site, scheduled activities, proximity to roads, buildings, trees and utilities lines. Accordingly, additional consideration must account for safety and the accessibility of deliveries, parking, materials and storage. Congested construction sites, shown in Figure 9 below, pose the risks of having crew members too close to moving equipment, and difficulty facilitating and coordinating the movement of equipment, materials and crews on-site (Spillane et al., 2011). Similarly, parking, storage and laydown areas require more strategic assessment to avoid additional costs for increased site monitoring and security. Insurance premiums may also be higher than normal if a higher level of risk is event (Isle of Wight Centre for the Coastal Environment, 2006).

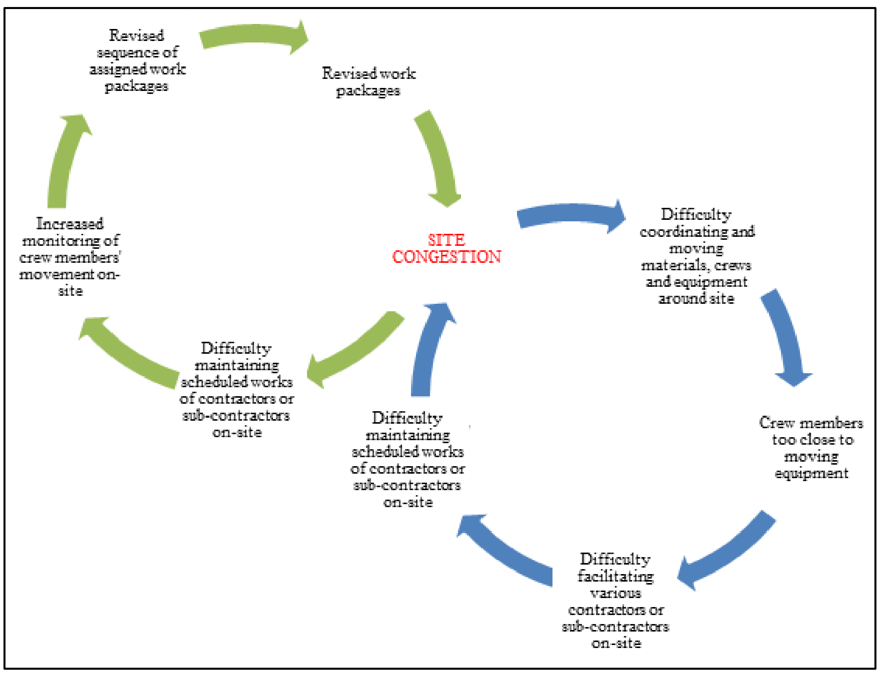

Figure 9: Causal Loop Showing Overcrowding Risks
(Adapted from Spillane, 2011)

Securing crews, equipment and materials for a project also poses significant risks as their availability may prove to be scarce or overpriced. In such conditions the project risks excessive delays and increased uncertainties. Furthermore, the experience level of the crew members is also a risk factor. Troyer (2011) explains the importance of providing training for crew members in relation to the potential hazards of the site; it must however be noted that experienced worker tend to pose the risk of negligence (Flanagan and Norman, 1993). The lead time for permits and experienced support technicians, such as utility locators, surveyors or regulation inspectors, can also derail a project. These risks may be avoided with preparedness and early investigations into the project location, regulations and suppliers. For example, Alberta One-Call, a provincially regulated utility location service, created the following utility location scenario flowchart, shown in Figure 10, explaining the lifespan of locates and the processes to be followed.

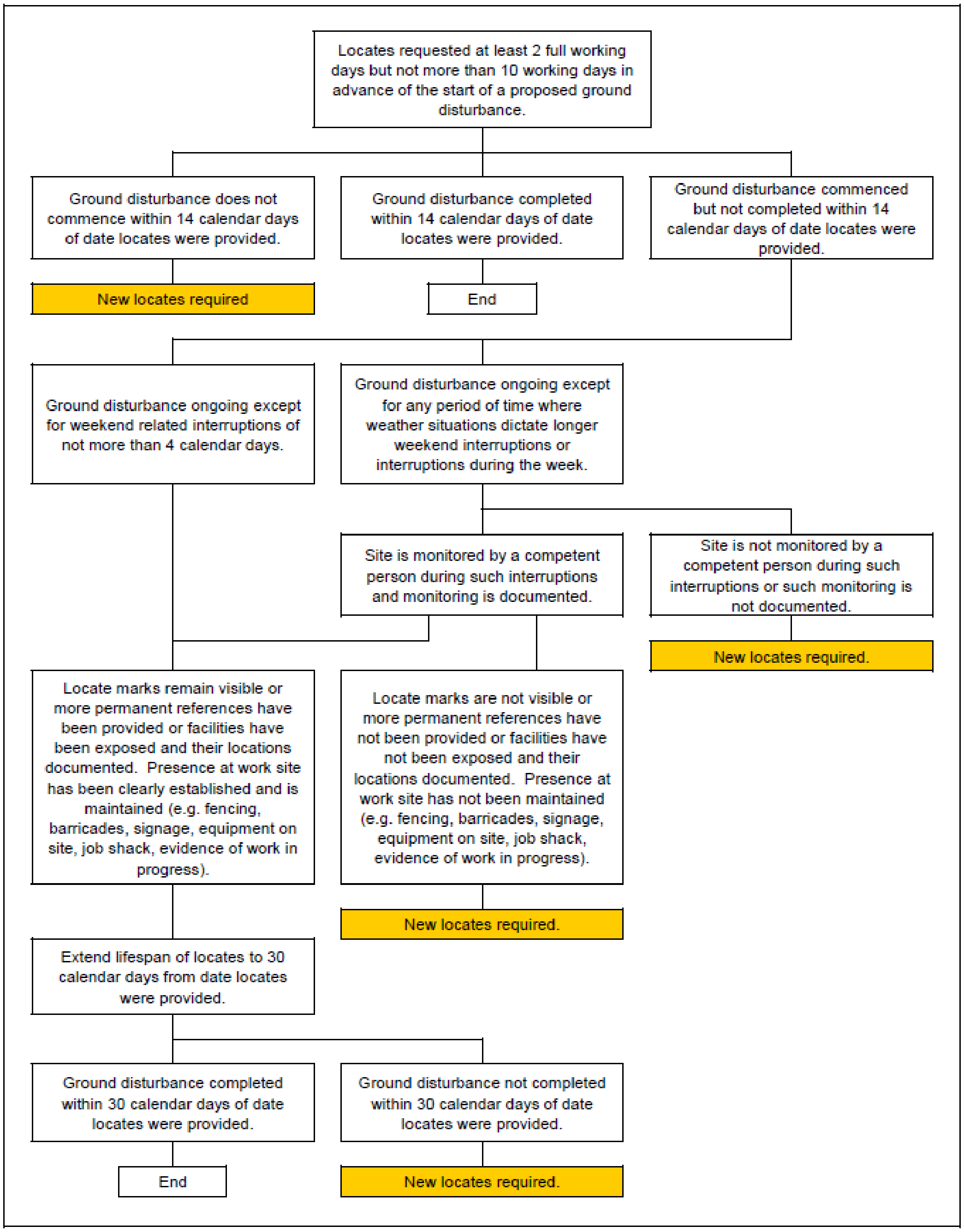

Figure 10: Alberta One-Call Locates Lifespan and Processes (2007)

Table 3 below is a comprehensive review of the risks associated with mobilization and demobilization on tunnelling projects as well as mitigation strategies extracted from the literature review and collected project data.

It is important to note that risk cannot be assigned a one-to-one mitigation; instead it is typical to try numerous mitigation methods before the appropriate one for the situation is identified. Furthermore, it is also common that mitigating one risk may create another, so it is best to list mitigation strategies used on categories to which they relate, rather than trying to complete a comprehensive list for each risk. This strategy of grouping the risks into categories and assigning a group of mitigation is used in the following risk register. It is recommended that the user of the register review all mitigation strategies suggested and apply the one best suited for that specific scenario.

Table 3: Mobilization and Demobilization Risks Mitigation

RISK	MITIGATION/CONTROL
Poor site layout/Site congestion • Insufficient space for equipment, parking, storage • Poor accessibility for emergency vehicle • Lack of available water, power and sanitary services on site • Inadequate space for launching pad, portal and/or shaft lay down areas • Inadequate working space inside the tunnel • Poor shaft locations	• Inspect site for and remove (if possible) exposed structures or hindrances that may affect equipment and crews • Consider the effect of alternative equipment to be used in lieu of larger models • Layout equipment in respect to schedule necessity and requirements • Utilize multitasking equipment • Minimize the space needed for parking and storage by implementing carpooling for crew members and/or offsite storage and parking • Maintain clear route through site for vehicles • Make arrangements for water, power and sanitary services to be set up on site once the contract is awarded • Utilize modular/offsite construction for applicable items • Inspect tunnel alignment and coordinate stable space for portal and shaft staging areas. Consider immediate access points to increase ventilation and mucking exits.
Crew (personal) injury • Personal injury or fatality of crew members and/or equipment operators	• Mandate wearing personal protective equipment (PPE) • Install alarms and lights on mobile equipment • Educate crews of hand signals for mobile equipment • Mandate the use of the “see and be seen policy” • Use flaggers
Lack of utility location survey • Damage to utilities and power lines • Personal injury (including electrocution) of crew members	• Contact a utility location service and/or owners to have lines marked, moved, de-energized or staked prior to work beginning • Mandate the use of protective equipment around utilities
Severe weather	• Geotechnical investigation to identify potential weak zones

• Ground instability • Landslide • Heavy snow or rain fall	• Erect fences and install signs and markers around weak zones • Install support systems to increase ground stability • Inform and educate crews of ground instability hazards • Arrange for site cleanup prior to site setup; consider rearranging scheduled activities to accommodate those least affected by severe weather • Consider utilizing a double shift during good weather to make up for loses in bad weather
Lack of or expired permits • Delays or shutdown • Fines	Ensure that all permits are obtained, accurate and kept up-to-date
Lack of an experienced crew • Shortage of skilled crew members	• Contact labour unions for skilled crew members • Provide training for crew members
Lack of equipment and materials • Shortage of equipment • Equipment maintenance delays • Delay in ordering/obtaining equipment • Delay in ordering materials	• Early investigations into location and suppliers. Consider the lead times for each and set up equipment and materials contracts once project has been awarded. Also factor in time for assembly and maintenance • Follow maintenance schedule for equipment. Pre-order commonly needed spare parts • Ensure the availability of skilled maintenance personnel
Ventilation for underground space	Coordinate ventilation for the underground works
Workplace Safety and/or lack of compliance to local and national health and safety regulations	Have an integrated workplace safety plan that has been approved by local safety authorities. Follow up with the implementation of the plan
Poor communication	Initialize the use of clear communication of the overall project requirements, responsibilities and expectations, as well as the emergency and evacuation plan

3.2 Excavation, Backfilling and Removal Risks

3.2.1 Excavation Risks

An excavation is any operation that uses tools or equipment to displace any material in the ground; it is typically used in construction for wells, shafts, trenches, tunnels, earthwork and underground works. Though seemingly simple, it is an extremely risky construction task that frequently results in injury, damaged property and infrastructure. In 2004, AXA, a large construction industry insurance provider in the United Kingdom, reported 37 fatalities directly caused by the ground collapsing during excavation works between 1997 and 2002. Similarly, the *Australian Code of Practice for Excavation* stated that trenching accidents directly related to excavation works accounts for almost 200 deaths annually. This report continued by noting that one cubic meter of soil typically weighs upward of 100 pounds, making escape difficult and thus leading to suffocation or asphyxiation. The Construction Risk Control Partnership (1999) lists these statistics about excavation risks and safety:

1. 1,000 - 4,000 workers are injured in excavation-related accidents annually
2. 80% excavation-related deaths occur in less than 15 feet, while 40% occur in 10 feet or less.
3. An excavation accident is 15 times more likely to result in death than any other construction incident.

OSHA's *Trenching and Excavation Plan* (29 CFR 1926.650 - 653) states that the most frequent risks of excavation include contaminated soil, injuries from and damage to utility service lines, structural collapses, drowning in ground or sewerage water, and exposure to hazardous substances, fumes and gases. The general public is also often at risk of falling into unattended or poorly documented excavated holes and also from falling debris.

Tunnelling excavation can be accomplished using numerous effective methods. The preferred method mostly depends either on the known soil or environmental conditions or on the desired outcome. Regardless of the technical advancements in tunnelling excavation the primary hindrances remain quite simple – rocks and other obstacles jamming or clogging mechanical devices. In *Case Histories of Trenchless Excavation*, Tarkoy (1994) describes boulders and rip rap as "encountered difficulties … surprisingly consistent in nature". Tarkoy continues to explain that boulders have the ability to completely stop or significantly slow production on projects using mechanized excavation methods.

With such references it is extremely necessary to address the common risks factors associated with tunnelling excavations. In an *International Tunnelling Association* research project, Ŝ ejnoha et al. (2009) concluded that between 40 and 75 percent of the total construction costs of a tunnelling project can be directly attributed to the cost of excavation, and is due primarily to geotechnical conditions. The report continues by stating that tunnelling construction risks can be classified into groups: (1) unfavourable geotechnical conditions; (2) incorrect design and planning; (3) incorrect execution; or (4) a combination of the previous three.

Unfavourable Geotechnical Conditions, Incorrect Design & Planning and Incorrect Execution

Unfavourable geotechnical conditions or unstable ground conditions has been labeled the greatest risks to tunnelling construction in the FHWA's 2011 publication titled *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*. Figure 11 below, adapted from Clayton's (2001) investigation of 28 construction projects, shows the typical geotechnical problems that occur during tunneling construction.

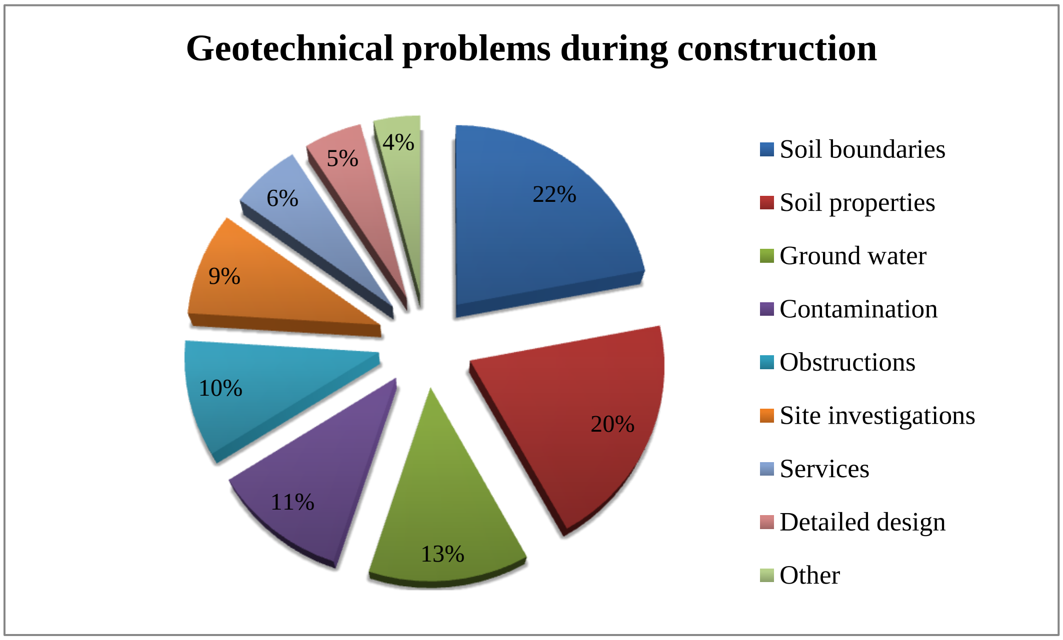

Figure 11: Geotechnical Risks during Construction (Adapted from Clayton, 2001)

Soil properties, a substantial portion of Clayton's investigation, depict unfavourable ground conditions. Though not always required, it is good practice to conduct soil borings prior to excavation to determine the soil structure, rock mass and other geological characteristics of the ground. However, it should be noted that soil borings will not provide complete information on ground conditions. In January, 2005 in Barcelona, Spain, a tunnel being excavated for the Barcelona Metro collapsed causing damage to surrounded buildings, including local businesses and residential homes. This incident was categorized as a geological oversight during excavation that resulted from an undiscovered fault line in the unstable clay terrain surrounding the excavation. The subsequent gorge, reported as measuring 30 meters wide and 35 meters deep, swallowed nearby buildings and properties.

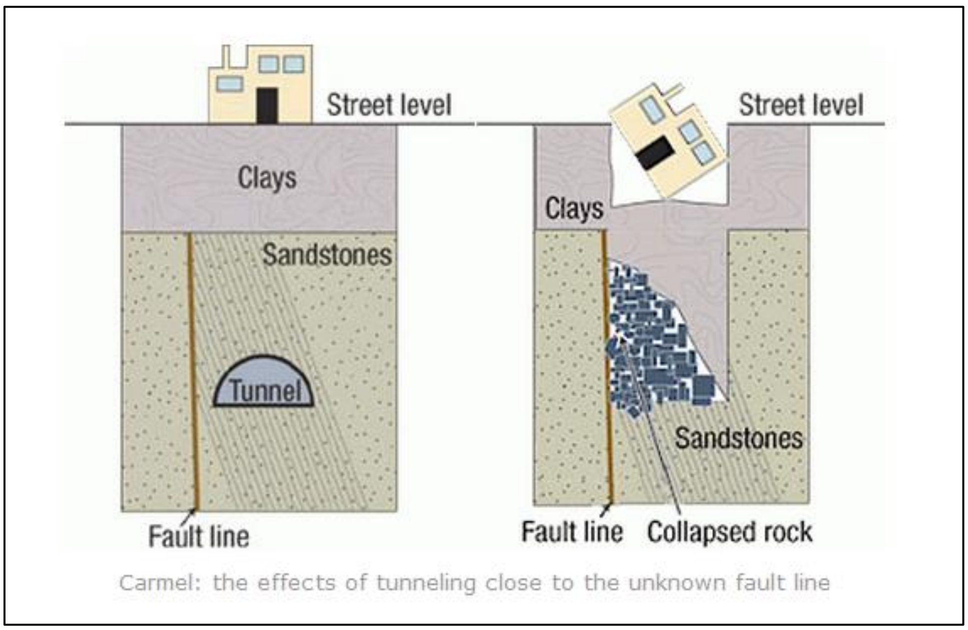

Figure 12: Illustration of the Tunnel Collapse in Barcelona, Spain, (*Barcelona Field Studies Centre, 2005*)

As a result of this collapse, the Barcelona Field Studies Centre reported that approximately 1,000 residents were made homeless, 15,000 people were affected and that several severely damaged building had to be demolished. Subsequently, the city's parliament ordered the project's stakeholders to re-house the displaced residents, the tunnel was filled with concrete and the project abandoned. To avoid these results, the FHWA's (2011) technical manual advices that if fault displacements are unavoidable or unknown it is best practice to mitigate displacements by using oversized excavations backfilled with compressible/collapsible material, or by using ductile lining to minimize the potential instability.

Unexpected groundwater is also an unfavourable geotechnical condition in tunnelling construction. Seidenfuβ (2006) suggests that groundwater levels can be affected not only by soil conditions, but also by man-made conditions resulting in obstructions to the task and safety hazards to the crew. Water penetrable soil loses much of its stability and strength causing collapses or cave-ins of excavation roofs and walls. Also, water inrush in mechanical devices can be critical, especially if the tunnel is headed downhill or starting from a shaft. Instability due to excessive groundwater pressure or flow can occur in almost any rock mass but typically required involvement with other conditions to increase severity. Nevertheless, if water is flowing towards the tunnel's working face, even a small amount may be enough to permit the start of a run that can develop into total collapse.

Dewatering is the diversion of water away from an excavation in an attempt to secure its stability. Care should be taken so as to not dispose of water removed from excavations near or in another work zone, or in an area where it may cause damage to other surfaces or property. These precautions may include the installation of a water pumping device, pipes or other channels deferring water away from the excavation site. The City of Edmonton's *Design and Construction Standards* (2009) states that in order to prevent waterlogging excavations should be maintained at least 0.5m above the water table and proceeds to discuss optimizing the elevation of capacity of a backup water removal system in order to minimize the risk of flooding.

Similarly, contaminated groundwater in tunnel excavations, depending on severity, need to be collected and treated prior to being disposed of. Severe contaminations may ignite concerns regarding explosions or fire hazards in the tunnel, chemical contaminants, and/or fugitive emissions of contaminants into the environment. For example, gassy soils, though typically the result of a fracture, break or leak of a utility line, may occur naturally in deep excavations and may release some hazardous gases. Environmental contamination deserves much consideration during excavations not only to satisfy environmental regulations, but also to ensure the crew safety and project stability. In contaminated soils it may also be necessary to fit excavation equipment with non-sparking buckets or blade to avoid ignition of vapours encountered in the hole. The Department of Transportation's *Specification for the Reinstatement of Openings in Highways* (2010) states that any excavated material "which is deemed unstable, unsuitable or unnecessary for backfilling should be removed from the site as soon as practicable to minimize contamination or safety risks".

ITA (2010) discusses other major concerns for tunnelling construction which include squeezing, bursting and swelling ground, all of which are due to high in-situ stresses. Squeezing and swelling ground causes deformations in rocks;

swelling is an inverted deformation. In addition the ITA identifies the poor ground strength and high water pressure (face instability) that often results from tunnelling in or near fault zones. Similarly, Seidenfuβ (2006) explains that karstic voids, typically found in fault or tensile fracture zones, are natural caverns or sinkholes. The stresses created surrounding these zones may lead to soil erosion, declined soil strength and sinkholes through which water can enter the tunnel.

Seidenfuβ (2006) further investigated collapses in tunnelling construction and concluded that the errors made by "unqualified or wrongly deployed staff" were immeasurable. It was, however, identified that the combination of incorrect planning and execution was often worsened by unfavourable geotechnical conditions. For example, it is common practice to utilize ground freezing in fault zones to avoid the potential inflow of water (unfavourable geotechnical condition). However, if the ground freezing pipes are incorrectly installed (incorrect execution) then the monies and time spent on geotechnical investigations can be deemed wasted. Consequently, each classification must be thoroughly accounted for.

3.2.2 Backfilling Risks

Backfilling is usually done immediately after the removal of the support system and workers are not permitted into unprotected excavations, regardless of the reason. Backfill is typically the same soil removed during excavation. One of the biggest risks involved in backfill is the stability of the soil once backfilled. The problem exists because during excavation air, resulting in voids is mixed into the soil. Regardless of being compressed these voids still exist and are the perfect locations for water to accumulate. To remedy the problem of water saturation in backfill it is common practice to top backfilled soil with compacted clay.

If pipes or utility structures are present in the excavation hole, it is most important to realize that backfilling introduces significant loads to pipes and utilities. The following points must be observed to maintain the integrity of and minimize the risk to the pipes, utility lines and the backfill material (Nagadi, 2008).

- Ensure that the ground supporting the pipes is adequately sloped and leveled to minimize warping or sagging of the pipes. Backfilling and compaction will lock the pipes in place and warping may cause damage or leaks.
- Direct contact with excavation or backfilling equipment may cause breaks or cracks in pipes and utility lines. Verify the compaction and weight limits of the pipes or utilities and compare with equipment being used.
- Backfill must be placed consistently and systematically to avoid de-aligning pipes and utilities. Initial backfill on both sides and the base of pipes and utilities may require hand-filling until pipe stability is ensured.
- Use pedestrian rollers set to the requisite level for initial compaction and tests prior to using construction-sized compaction machines and loads over backfilled area.

Other than injury to crew members the major risk associated with dirt removal and backfilling is that of damaging utilities, including water mains, sewerage and drains, gas lines and telecommunication, electricity and television cables. Backfilled soil must be compressed to ensure structural stability, but special consideration must be observed around utilities. As mentioned previously one cubic foot of soil weighs approximately 1000 lbs.; even the strongest utility pipes may be fractured, broken or bent if this weight is poorly placed on it.

The following table, Table 4 summarizes the risk factors associated with Excavation and Backfilling and shows mitigation strategies for the risks.

Table 4: Excavation, Backfilling and Removal Risks Mitigation

RISK	MITIGATION/CONTROL
Differing geotechnical conditions • Unexpected ground conditions, including large boulders and different types of soil • Undiscovered/unaccounted fault lines • Larger than expected settlements	• Conduct additional geotechnical investigations and treatments • Have a mitigation plan for unexpected encounters with boulders, including the use of different equipment or hand tunnelling • Use oversize excavations and backfill with compressible/collapsible materials or use ductile lining to minimize instability • Use a special monitoring system and consolidation measures to account for settlements prior to passing the TBM • Either check for variation of vertical and horizontal tunnel alignments, or utilize underpinning, compensation grouting, etc.
Gassy ground • Exposure to hazardous gases	• Use of gas masks by crew members • Use of gas monitoring devices and detector systems for the anticipated gas types (i.e. toxic, flammable, etc.) • Neutralizing chemical compounds or absorbent materials • Use of sufficient ventilation systems to provide fresh air to the TBM and face area • Drilling holes in area of the potential source for gas drainage • Have access to a contamination clean-up crew
Squeezing and swelling ground • Large ground deformation around tunnel	• Avoid over excavation or additional circumferential cutting • Use of lubricants such as bentonite, grease • Re-schedule machine maintenance to avoid long stoppages and prevention of machine break downs • Use auxiliary thrust system

Encountering fault zones or karstic voids	• Drill drainage holes to relieve high water pressure • Fill in karstic voids • Investigate fault lines in the area and take precautionary measures nearby • Probe drilling • Ground freezing • Use of shielded TBM
Groundwater inconsistencies • Groundwater breakthrough from excavation hole cause flooding • Groundwater foundation is too thin • High groundwater pressure • Seepage • Inadequate handling of water conditions • Handling of slurry muds • Free flow of water • Leakage between tunnel segments	• Use systematic probe drilling and deep boreholes to prevent face instability • Investigate the rock types present to deduce groundwater levels • Utilize empirical databases to predict groundwater levels and temperatures in project area • Utilize water absorbing materials to keep work site dry • Utilize ground freezing, slurry cutoff walls and/or grout curtains • Use of segmented lining and grouting behind the segments for water tight sealing • Drainage using open or closed channels, as well as pumping the water through drainage pipelines • Use of shielded TBM with bulkhead or pressurized face • Excavate at a slight upward slope so groundwater drains away from work area
Severe weather • Heavy snow or rain storms • Landslides	• Optimize productivity during good weather to increase the availability of float time during bad weather • Arrange snow removal prior to beginning work; setup heaters where possible • Rearrange schedule to accommodate tasks not affected by severe weather

Wall instability encountered by open TBMs	• Tunnel lining with precast concrete segments • Use of shielded TBMs • Use of support systems such as steel arches installed behind cutter head, shotcrete, rock bolts, steel straps, and wire mesh • Pretreatment by injection holes
Environmental impacts • Excessive dust • Vibrations and Noise • Contamination of groundwater or ground	• Specific PPE for crew members • Develop schedule to measure air quality and utilize a dust mitigation plan • Regular medical exams for crew members • Ensure surrounding areas are adequately supported • Monitor nearby structures for signs of impact due to vibrations
Explosions or fires during excavation • Spark from contact between equipment and flammable fumes, rocks, buried metals, etc.	• Utilities should be located and marked prior to excavation. • Excavation equipment may be equipped with non-sparking buckets or blades
Electrocution of crew members • Excavation equipment ruptures electrical utility	• Utility location prior to excavating • No mechanical excavating within 2 meters of location of marked utilities • Mandate wearing PPE
Utility damage • Unexpected existing utilities • Damage to utilities and power lines • Personal injury (including electrocution) of crew members	• Contact utility One-call service and owners to have lines marked, moved, de-energized or staked prior to work beginning • Mandate the use of protective equipment around utilities • Increase in-house surveying prior to excavation
Encountering of prehistoric artifacts or fossils	• Conduct a preliminary investigation of site history • Stop work and report findings to local authority • Assist in excavation of findings so as to expedite resumption of work

Internal corrosion of pre-cast concrete lining	Utilize a corrosion protection lining (CPL) system
Excavation roof or sidewall collapse	• Fill sidewall cave-ins with stone and shotcrete • Grout to prevent the void from collapsing

3.3 Equipment Risks

Conventional drill and blast methods use standard construction equipment including backhoes, jack hammers, excavators, bulldozers and hauling units (scraper, muck cars, off-road trucks, or highway trucks), however, with bigger projects needing expedited development, today's industry is more mechanized with the use of such equipment as tunnel boring machines (TBMs) for large tunnels and hydrovacing becoming common practice for tunnelling construction. Accordingly, tunnelling by TBMs and other complex mechanized means are expected to experience more equipment risks that those faced by conventional drill and blast methods. Subsequently delays and other associated hazards are also expected to reap larger cost penalties in mechanized tunnelling rather than conventional.

Regardless of the methods chosen and the sophistication of the equipment being used, tunnelling construction sites are typically plagued with similar equipment risks. These risks include the overturning of equipment, crew members being struck by equipment, equipment parts failing due to lack of maintenance or crew member being caught in the path of moving equipment. The severity of these risks varies from near-misses or minor cuts and scratches to fatalities.

The Off-Highway Plant and Equipment Research Centre (OPERC) stated that one of the most common risks for tunnelling construction equipment is the collapse of excavations or trenches under or close to the machine's tracks, resulting in overturning or instability. Another hazard outlined by the OPERC is the risk of personal injury to crew members and site personnel within the operating area of machinery caused by:

- Operator lack of visibility of other crew members;
- Excessive loads and extensions causing overturning or failure of equipment parts, resulting in damages to the project and the machine;
- Working too close to edge of excavations, benches or ramps;

It is recommended that large obstacles, weak ground and severe inclines be avoided when using tunnelling equipment. O'Sullivan (2011) emphasizes that if these situations must be encountered, precautions including fitting the equipment with safeguards, increasing the load capacity of working pads and keeping excavator tracks parallel to benches must be taken to ensure safety. Additional provisions may include increasing the load capacity.

Poor equipment maintenance also poses the risks of equipment failure resulting in crew members being struck by detached or uncontrollable parts. Crew members also fall victim to perfectly maintained equipment. Statistics show that 22% of injuries and deaths on construction sites occur from a crew member being struck by equipment, while 18% results from crew members being caught in-between equipment (Construction Risk Control Partnership, 1999). Consequently, all tunnelling construction equipment should be equipped with backup alarms to notify crew members. Furthermore, *Health and Safety Ontario* (2011) reports most construction sites now utilize the "see and be see policy" in which the operator cannot move equipment without having a flagger or being able to see all crew members, and verify that he/she is being seen.

Equipment manufacturers have also taken the initiative to inform crew members and operators of the hazards of mobile equipment. For example, the *Bobcat Company* frequently publishes a list of hazards, risks and mitigation guidelines, shown below in Table 5.

Table 5: Sample of Bobcat's Excavator Risk Assessment Table

	Hazard	Risk	Severity	Mitigation/Control
1	Untrained in operation and safe work procedure	Operator or bystander death, equipment damage, roll machine	High	All operators must be authorized and require excavator license - otherwise breach of OH&S Act.
2	Bystander run-over or impacted by boom arm/bucket	Death or crush/serious impact injury	High	Bystanders to be kept well clear at all times. Motion alarm, mirrors and beacon lights fitted.
3	Poor maintenance of excavator	Failure of structure - death	Med- High	Ensure correct maintenance is undertaken and recorded
4	Overloaded excavator tipping over	Strike Injury	Med- High	Rating Plate check by operator
5	Tip-over due to turn on gradients unsafely	Tip-over cause operator strike injury	Med- High	Do not turn on an incline re: O&M Manual
6	Cabin structure failure	Operator crush/strike injury	Medium	Workplace hazard analysis - machine should not be operated in such conditions
7	Safety decals missing	Staff not aware of dangers - injury	Medium	Ensure maintenance staff replace any missing of un-readable safety decals
8	Hose splits and sprays hot oil	Burns to operator	Low	Operator protected by cabin and/or 'burst bags' from spray. Never check for leaks with hands.
9	Noise - hearing damage	Permanent hearing damage	Low	Machine low noise, especially in cabin
10	Vibration	Vibration injury to operator	Low	Padded suspension seat fitted. Machine operated stationary. Control pilot oil controlled.

Another risk is that of difficult ground conditions. It is important to ensure that the equipment being used is suited for the surrounding environment. The *Irish Health and Safety Authority (2002)* suggest the following mitigation to control hazards involving mobile equipment:

- Plan equipment routes on-site by taking in account overhead wires, excavations and other hazards.
- Limit the number of vehicles and equipment allowed on site or around a specific construction area.
- Set and enforce appropriate speed limits.
- Minimize activities requiring equipment to reverse. When necessary use reverse alarms, flashing lights, reverse cameras and/or mirrors.
- Provide signage and instructions around construction site.
- Use a flagger.
- Ensure that construction site is well lit.
- Train crew members and operators in the use of hand signals and a safe work plan.
- Equipment operators are required to wear seat/safety belts as per equipment operator's manual recommendations.
- Maintenance checks (including lock-pins, valves, releases and fuel lines) should be carried out daily before the use of any equipment.
- Supervisions, monitoring and frequent checks must be carried out to ensure compliance with equipment, project and federal safe work procedures.

Table 6 below is a comprehensive review of the risks associated with equipment on tunnelling projects as well as mitigation strategies from the literature review and collected project data.

Table 6: Equipment Risk Mitigation

RISK	MITIGATION/CONTROL
Operator uncertified or untrained in safe work procedure	All operators must be authorized and require excavator license - otherwise breach of OH&S Act.
Untrained crew members • Inadequate crew interaction and understanding of equipment	• Crew members must be provided with training associated with the task and equipment being used • Motion alarm, mirrors and beacon lights fitted on all equipment
Poor maintenance or assembly of equipment • Equipment failure • Inaccurately coded/marked equipment • Survey errors	• Ensure correct maintenance is undertaken and recorded • Ensure maintenance staff replace any missing of unreadable safety decals • Verify calibration of survey equipment • Use only certified surveyors
Unsafe use of equipment	• Rating Plate check by operator. Do not turn on an incline re: O&M Manual. • Workplace hazard analysis describing proper use and care of equipment • Use of appropriate PPE around equipment
Lack of access in and out of work areas • Congestion and working in confined spaces	Review site layout and task coordination
Poor maintenance of traffic practices	• Provide barricades and markings directing traffic around site or fence in work area • Crew must wear traffic-specific PPE
Utility damage	• Locate all utilities prior to using equipment • Use only equipment suited for use around utilities • Allow float time for use of hand digging around utilities • Obtain permission from utility owners to use certain equipment around utilities

	• Report all instances of damage to utilities • Crew members must wear recommended PPE
Vandalism	• Returning tools to lock-boxes • Lock/secure equipment after use
Difficulties maintaining alignment and tolerance	Use laser technology with other surveying techniques to aid in alignment
Lack of control of face stability	Use earth-pressure balance shield machines

3.4 Pipe, Manholes and Gates Installation and/or Removal Risks

3.4.1 Pipes

Pre-existing pipes are often damaged during excavation for open-cut construction. It is crucial to keep mechanized excavation equipment at a two meters distance from located pipes and utilities to avoid damaging pipes with heavy machinery. Within the two meters hand tools should be used to minimize potential damage to pipes and utilities, as well as to increase the opportunity to identify other hazards in the immediate area.

The excavation slope, backfilling load and the trench width and size are as important as the actual pipe strength and must therefore be considered to avoid damage to the pipes. The excavation must be sloped consistently to avoid bends, stress points or warping of pipes. The backfilling load, if poorly re-introduced into the excavation, may cause breaks or cracks in the pipe, thus leading to future damage. In some cases the excavation width is too narrow to allow useful access of the excavation machines, which commonly leads to trench wall breakdown and other risks outlined in the excavation risk section of this research. Oversize trench widths are also hazardous. In those cases where the trench width is not expressly specified, T. Nagadi *Preformed Concrete Factory* (2008) suggests using as narrow a trench as possible for excavation "with side clearance adequate enough to insure proper piping installation and compaction of backfill material at the sides of the pipeline" to minimize hazards. Relatively, OSMA (2005) recommends openings no less than 300 millimeters wider than the pipe diameter.

The American Concrete Pipe Association provides manuals for concrete, HDPE and SRHDPE pipe installation techniques including details on excavation limits, trench and embankment standards, joint procedures and backfilling.

With environmental considerations, cost factors and time restrictions other risks associated with pipe installation and removal exists; including technological advancements. Pipe ramming, for instance, is a trenchless pipe installation method used to pneumatically hammer pipe or steel casings into difficult ground conditions, while directing spoils for removal on the surface. Simicevic and Sterling (2001) assert that though directional drilling is better suited for long bores, pipe ramming is typically more cost and time effective for bores between 5 and 60 feet for large pipes at shallow depths. The primary risks associated with pipe ramming are the loss of time and subsequently more if extremely difficult ground conditions, including extra-large boulders, are encountered and the risk of encountering other, potentially active pipes, lines or utilities. In such cases prior bore tests and utility location, the use of thick-walled steel casing or a hammer to break obstructions is usually adequate mitigation.

Open-cut construction is the conventional pipe installation and removal technique. Its procedure continues to excel in its simplicity: digging a trench, laying pipes inside, and filling in the hole. Regardless of its tried-and-true heritage, open-cut construction is not suited for all pipe-installation, such as below roads or infrastructure. In today's society its lack of the ability to have little or no environmental or social impact is open-cut's primary downfall. Accordingly, much research and advancements have been made on trenchless pipe-installation methods.

Though countless other trenchless methods exist, horizontal directional drilling (HDD) has become one of the preferred methods of installation for pipe crossings. Credited as an extremely low-impact construction technique, HDD is applicable to the installation of pipelines under roads, utilities, waterways and other obstacles. With adequate planning, HDD can be a cost-effective pipe installation method for almost any tunnelling scenario.

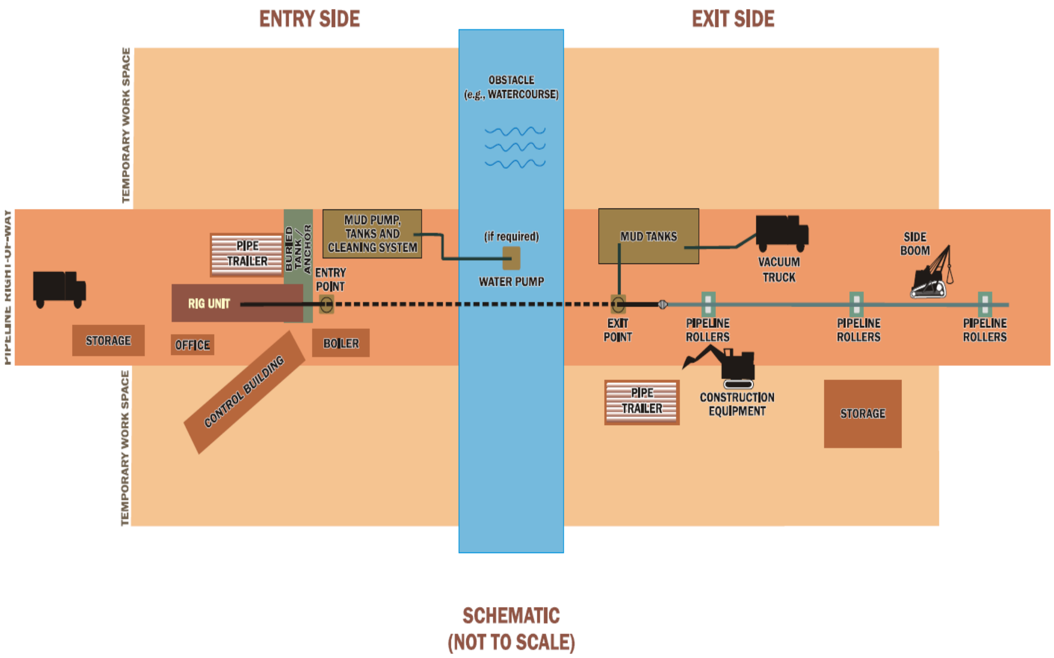

Figure 13: Schematic of Horizontal Directional Drilling (Canadian Association of Petroleum Producers, 2004)

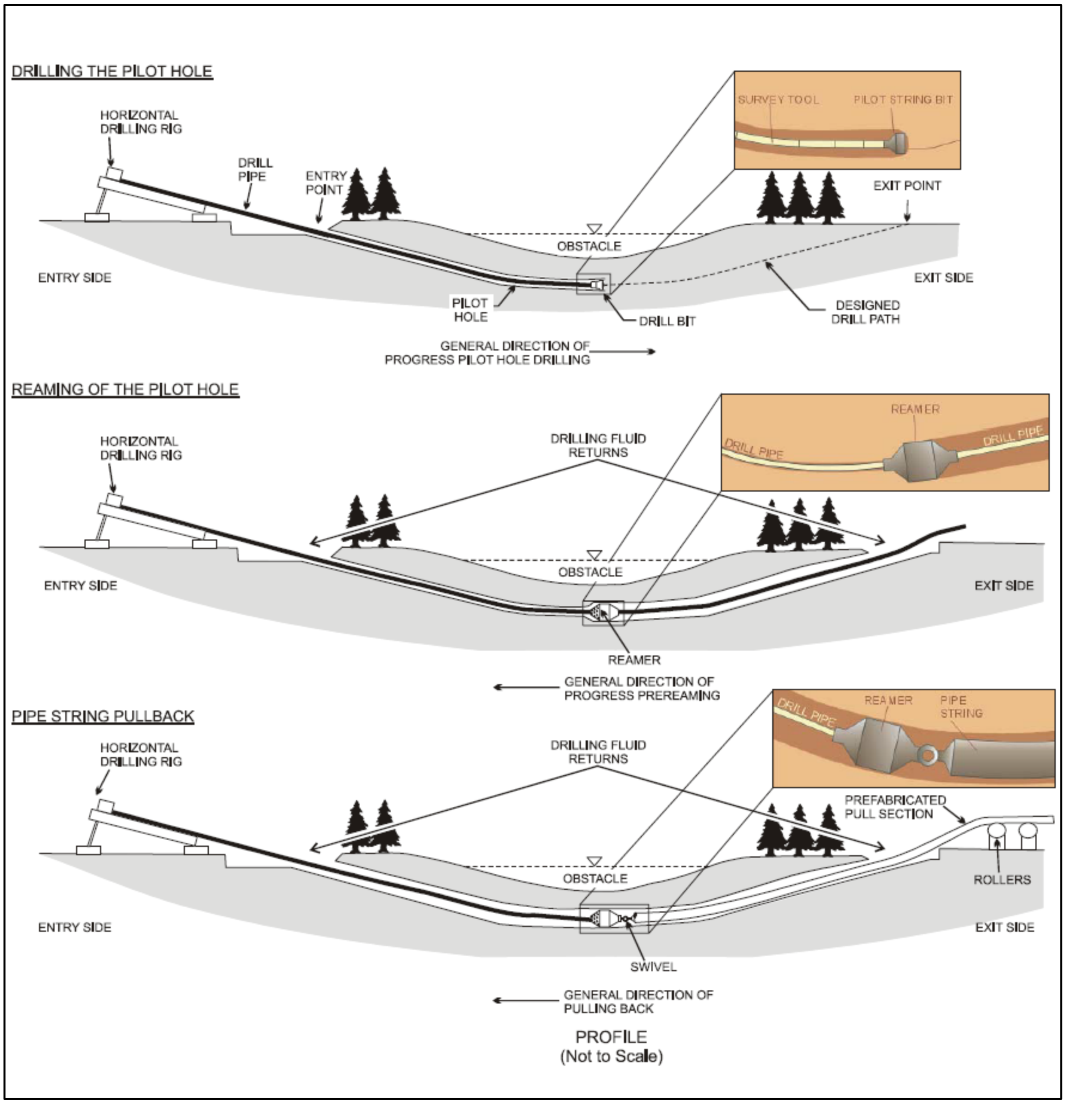

Figure 14: Schematic of Horizontal Directional Drilling (Canadian Association of Petroleum Producers, 2004)

The main risks of HDD are associated with extremely difficult ground conditions, equipment breakdown or maintenance and damage to pipes. Detrimentally, the failure of a HDD bore may cause the highest cost and time overrun on a project. Accordingly, HDD is usually assigned the highest priority on a risk matrix.

3.4.2 Manholes and Gates

During pipe installation manholes may be required at changes in pipe material, size, grade, direction and/or elevation. The risks associated with pipe installation includes maintaining pipe stability and the need of excavation wall supports, but also includes added safety precautions for hoisting rigging and trench ventilation if necessary, ladders, personal protective equipment and training in manhole installations.

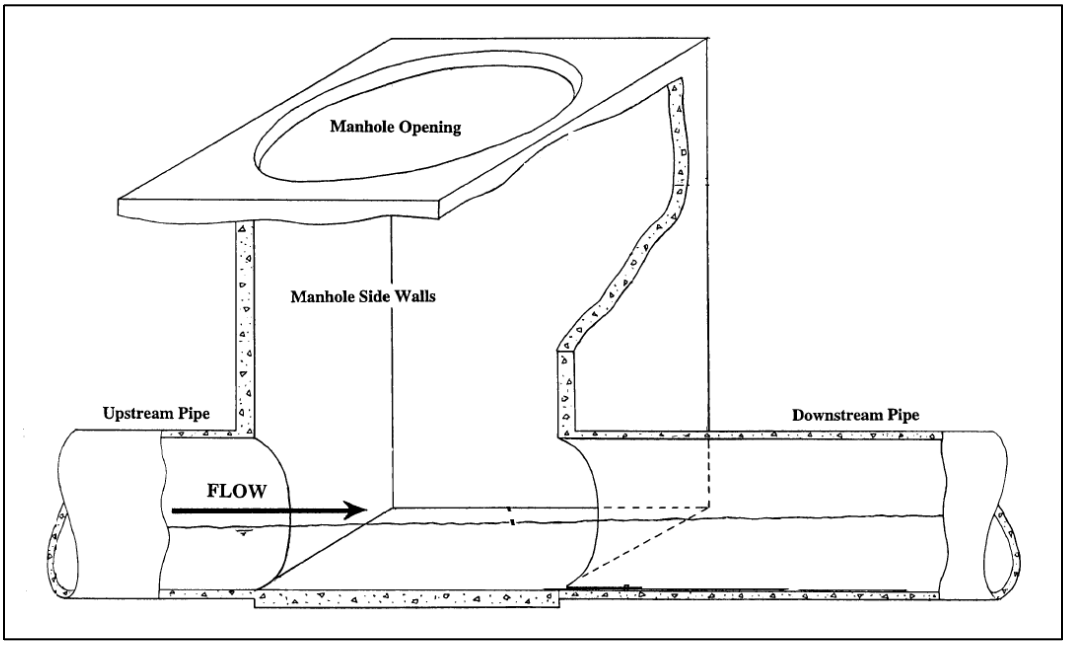

Figure 15: Illustration of Manhole at Stormwater Pipe Connection (Adapted from Maheepala, et al. 1998)

Figure 15, above, shows an adaptation of Maheepala's (1998) illustration of a manhole at a stormwater pipe connection. The utility box from the original figure was removed to clearly show the manhole and pipes.

The following table, Table 7 summarizes the risk factors associated with Pipes, Manholes and Gates and shows mitigation strategies for the risks.

Table 7: Pipes, Manholes and Gates Risks Mitigation

RISK	MITIGATION/CONTROL
Equipment too close to excavated holes • Cave-ins or collapse of equipment and excavation walls into excavation hole • Personal injury or fatality resulting from cave-in	• All equipment must be at least 2 meters away from the edge of excavation holes. • Shoring and other structural support for excavations deeper than 5 feet. • Access and egress for all excavations.
Utility location and relocation • Damage to pre-existing utilities and power lines • Personal injury (including electrocution) of crew members	• Contact utility One-call service and owners to have lines marked, moved, de-energized or staked prior to work beginning • Mandate the use of PPE around utilities • Support pre-existing pipes and utilities during excavation • Coordinate utility relocation with float to ensure proper handling
Ground instability	• Geotechnical investigation to identify potential weak zones • Erect fences and install signs and markers around weak zones • Install support systems to increase ground stability • Inform and educate crews against ground instability hazards
Difficult ground conditions • Delays, damage or cost overrun	Geotechnical analysis and the use of appropriate equipment.
Falling debris	Mandate no crew members in excavations without appropriate protection when mechanical equipment is being used overhead
Flooding in excavation hole	• Backup drainage pump must be on-site incase water accumulates in excavation hole. • Crew members must wear appropriate PPE if water is present or possible in excavation.

Risk checklist

As previously demonstrated the risk registers, shown in Tables 3 through 7, are compilations of the consensuses from a thorough investigation into the risks associated with the critical path of tunnelling construction projects. The risk checklist was developed to work in conjunction with the risk registers to assist owners and contractors identify the risks associated with their tunnelling construction projects by offering a straightforward method of reviewing the risks. Though the questions in the checklist could easily be dismissed with automatism, for best results it is recommended that users of the checklist consider the questions as a trigger mechanism initializing more thorough investigations. For example, when preparing for a task a foreman should not begin and end by only asking himself whether or not the crew is aware of an upcoming activity. Alternatively, the question should prompt the foreman's investigation into whether or not the crew has had sufficient training for the activity or if specialized personal protective equipment (PPE) is required, available on site and in proper working order. Once satisfied with that checklist question, the user may proceed to the next. At this point it should be emphasized that, as previously demonstrated, the checklist questions may seem repetitive. However, to be comprehensive and cover the different scenarios the checklist includes questions that may have already been triggered by a previous question by using the format demonstrated in the Construction Risk Control Partnership (1999) to ensure a concise and clear presentation.

1. Has the site been inspected by a project manager for conditions or exposed structures that may cause hindrances or other hazards prior to the arrival of any equipment or the beginning of the project?
2. Has the crew been advised of potential hazards and the associated procedures to be followed?
3. Are crew members utilizing personal protective equipment, as necessary? Is specialized PPE available and accessible?
4. Have flaggers and spotters been trained for utilization in the placement of large equipment and for interference with the pedestrians, general public and traffic?
5. Have all permits been approved and received? Are all permits up-to-date?
6. Has a preliminary investigation been conducted to identify the existence of any artifacts in the vicinity of the project? If so, have necessary permits been acquired?
7. Has a construction fence been erected around the perimeter of the project?
8. Have construction signs been used to draw attention to the construction area, potential delays, and other activities that may affect the public?
9. Are signs, placards, gates and other markings being utilized around the perimeter of the site and in areas identified within other risk assessments – such as around excavations?
10. Have the locations for crew parking, deliveries, storage and sanitary facilities been laid out on the site?
11. Are safety and security measures installed around job site?

12. Have all utilities companies been alerted of the work and located, marked and protected their utility lines both overhead and underground?
13. Has arrangements been made in advance to de-energize, move or install protective sleeves on overhead power and utility lines?
14. Have potential weak zones been identified and mark as a result of a geotechnical survey?
14. Have all equipment had a maintenance check (as per manufacturers recommendations)? Is there spare parts, oils, etc. available on-site or close by for equipment maintenance?
15. Are all warning devices/systems operational?
16. Is supervision on site to ensure and maintain compliance of safe work standards?
17. Have all safety issues been addressed and discussed with crews?
18. Is there a designated area set up for spoils, contaminated materials and unused equipment? Is it away from the immediate work site and accessible?
19. Are access and egress routes from excavations provided and accessible?
20. Have all applicable environmental regulations been accounted for and satisfied?
21. Has a geotechnical investigation been carried out? Does it account for the presence of groundwater, weak zones and soil stability?
22. Has the typical type of rock expected in the area been assessed?
23. Have site surveys been conducted?

24. Is there a severe weather plan? Is there preventative or reactive equipment and materials accessible for use in severe weather?
25. Has a risk register been initialized and updated for the project?

CHAPTER 4

VALIDATION

Validation aims to ensure that the planning, execution, and evaluation phases of the research truly reflect the highest standard of quality of the industry. The validity aspect of this research project was divided into three sections – content validity, criterion validity and face validity. Content validity is achieved if the parameters of the research, such as tasks and environmental conditions, are accurate representations of those typical in industry. To ensure content validity of this research the author reviewed the schedules of four large tunnelling projects that have begun in Edmonton, Alberta within the past 3 years, the last of which is expected to finish January 2015, and extracted the lists of items on the critical path of each project. The four critical paths were plotted against each other and the overlapping tasks were made the primary subjects for this research. As the remaining tasks are still critical and could therefore not be overlooked they were grouped into categories based on similarities and analyzes in groups. The next step was criterion validity which Lucko and Rojas (2010) define as the ability of these results to be successfully compared to that of similar research. Face validity is the final step in this validity inspection and is the subjective judgment of non-statistical nature that seeks the opinion of non-researchers regarding the accuracy and quality of the study. This phase in the research process therefore required the inputs and collective approval of industry experts as to the study and its results being a true representation of reality.

4.1 Content Validity

Content validity ensures that the parameters of this research are accurate representations of those typical in industry. For this project, the content validity was initially achieved by reviewing the schedules of four large tunnelling projects in Edmonton, Alberta. The critical paths of these projects were plotted against each other and the overlapping tasks were deemed critical and made the subject of this research.

The critical path was then investigated via a literature review that identified areas, outside of the projects studied, that required further investigation in order to accurately represent the current state and technologies of the tunnelling industry. For example, though having previously been encountered, karstic voids are not commonly found in Alberta’s soils and did not show up in the review of the projects from Edmonton. Thoroughness, however, required that all potential risks be included in the study.

The partial project schedules and reports of six additional international projects were also reviewed and similar information pertaining to the critical path of each project was also recorded. The critical path activities of each project were mapped onto each other and the consistently overlapping tasks became the scope of this research. Each of the critical activities was thoroughly investigated and consensus among risks and mitigations were recorded in the risk register. Inconsistencies regarding risks and mitigation strategies were investigated further until consensus was reached and recorded in the risk register.

4.2 Criterion Validity

Criterion validity is the ability of these results to be successfully compared to that of similar research. Much research has been done into identifying and analyzing risks of construction activities. Flores' (2006), for example, identifies, investigates and analyzes the state-of-the-art of tunnelling construction and created guidelines for managing risks from the viewpoint of the insurance industry. Similar to the author's research project Flores found that most industry personnel preferred to use simple techniques, such as checklists, to perform risk management on a construction site. Flores wrote that "the quality of a [risk management] system can be evaluated by the level of communication of risks among participants during the project …" Flores also addresses the impact of risk management practices outlined in the IRM's *The Joint Code of Practice for Risk Management of Tunnelling Works in the UK* and similarly comes to the conclusion that having a systematic procedure, when used in conjunction with a risk register is beneficial to tunnelling industry partners. Research also shows that many companies use their lessons learned as a method of improving the next project. Similarly, this research shows the usefulness of incorporating lessons learned, experience and technical hypotheses into a risk register so that mistakes are not repeated.

Loganathan (2008) continues on this idea of lessons learned by suggesting that bidders prepare, and submit in their bid, a preliminary geotechnical interpretative report (PGIR) to demonstrate their understanding of the geotechnical conditions, equipment, techniques and mitigations pertinent to the project and its location.

Though the delivery system of the PGIR differs from that suggested in this report, it embodies the premise that tunnelling construction is difficult and preparing for risk beforehand is the most useful risk management technique available.

Parker (2003) reports on the importance of conducting geotechnical investigations prior to any tunnelling construction works and discusses the vast impact the geotechnical uncertainties has on a project. Parker created tables to show typical challenges that can be expected on a tunnelling construction project and offers techniques on mitigating geotechnical uncertainties. Parker also points out the necessity of being knowledge of and prepared for tunnelling risks.

4.2.1 Stormwater Tunnelling Project Case Study

This Albertan highway interchange project was initiated in January, 2005 and completed in September, 2011 at $253.7 million dollars. The interchange was designed to alleviate the excessive traffic, collisions and congestion in the area as well as accommodate and improve the flow of the high volume of left-turning traffic at the intersection and to create safe accessibility to the surrounding neighborhood and businesses. With the new layout of the area, the increased stress on many of the existing pipes and the need for utility relocation, a new 1,400 meters long, 2,920mm diameter storm drainage tunnel was required for stormwater conveyance and storage. This tunnel was installed using a TBM.

The information shown below in Table 8 is a summary of the owner's consultant's preliminary risk analysis of this stormwater tunnel section of the interchange project. A summary of the risk factors and the critical path activity are provided, as well as mitigations. The risks identified in Table 8 correspond with the highest valued risk factors (500 - 2500 severity) in the construction phase as assessed by the consultant.

The risk analysis was then done for the same project by looking up in Tables 3, 4, 6 and 7. The results are comparable with the actual results of the preliminary risk analysis conducted for this project by a private consulting firm hired by the City of Edmonton. The results of the preliminary risk analysis are shown below in Table 8.

Table 8: Risk Factors and Mitigation Strategies from Stormwater Tunnelling Project's Preliminary Risk Analysis (City of Edmonton Project Website, 2011)

Preliminary Risk Analysis	
Risk Factors	**Mitigation Strategies**
Geotechnical condition worse than expected	Additional ground treatment
	More investigation of groundwater contamination
	Assess condition of pipeline cage, structural capacity and condition
	Provide site for on-site stockpile of contaminated material
Delay due to site logistics issues not addressed and resolved	Bring contractor in early to help facilitate constructability
	Conduct constructability review and prequalification
Disruption to businesses and motoring public	Maximize off-site production in design
Poor weather	Add float to schedule
	Improve drainage handling on site
	Use granular which can be placed during rain

Poor contractor relationship leading to cost overruns and delayed schedule	Partnership session
	Shared risk approach
	Proper and expedient responses to contractor questions and issues
	Competent field personnel
	Competent field superintendent
	Prequalification process
Relocation of utilities and/or pipelines may require shutdown/coordination	Put utility work in contract
	Advance utility design/construction to before contract
	Relocate on new alignment to avoid conflict
Insufficient contractor or material supply capacity	Alternate designs
	Separate contracts for roads and bridges
	Add one year to construction period
	Design to minimize materials

4.4 Face Validity

Face validity uses the subjective judgments of non-statistical nature that seeks the opinion of non-researchers regarding the accuracy and quality of the study. To accomplish this, the risk database was created from the preliminary risk analyses, followed by the actual risk management reports of four of the tunnelling projects. Furthermore, all supplementary information necessary to clarify or expand on the data came from scholarly papers and journal entries. To remain objective and to prevent biasing the industry personnel and non-researchers the author only discussed their professional experiences of risks, the industry standards and common mitigation techniques. Literature was only discussed with industry personnel in the form of questions about their experience in regards to a particular risk or event. Most of the initial responses supported the author's initial findings, while a few warranted further investigation or clarification. For instance, the author's third discussion with one of the industry professional focused on the ensuring the adaptability of this research into other markets. The suggestions warranted further investigation into geotechnical conditions and risks and adjusting parameters to match any local condition. Finally, the risk checklist and the mitigation database were discussed with the industry personnel to determine its usefulness, accuracy and quality and the author received positive feedback and interest in implementing the database on future projects. The risk checklist and the accompanying tunnelling risks mitigations proved to be credible sources of information.

CHAPTER 5

CONCLUSION

Risk is most commonly defined as the combination of the likelihood of a harmful occurrence and the severity of such an occurrence. The greatest severity in construction materializes on the critical path of the project and identifying and tabulating the critical path's most likely harmful occurrences and outlining mitigation strategies will reduce their impacts. The premise is that the risks that materialize outside of the critical path minimizes will have less damage on the overall project.

5.1 Contributions

This thesis provides access to the risks associated with tunnelling and incorporates best practices and prevention mechanisms into a risk register and a checklist. The risk register is a simplified and thorough compilation of risk mitigation strategies while the risk checklist provides a concise reiteration of the risks associated with tunnelling construction. The checklist works with the risk register, which draws attention to the common risks encountered on tunnelling construction projects, thus ensuring that they have been or are being considered and addressed.

Ideally, the checklist and risk register verify understanding of the risks associated with tunnelling construction and expedite verification that the typical risks have in fact been accounted for, addressed and agreed upon by owners and contractors. The checklist and risk register developed in this research can now be used as guidelines for tunnelling risk management. However, the checklist and database are in no way intended to substitute practicality or override judgments; they are to be an accessible source of useful information pertaining directly to known risks. It should also be noted that though not all risks are recorded in the database or accounted for on the checklist, nor can they ever be, the checklist and database can serve as a learning tool.

Though most of the research conducted for this project is based on Canadian/North American tunnelling practices and technologies, numerous references for this research were acquired from the Europe, Asia and South America to ensure worldwide adaptability.

5.2 Limitations

This research involved many theoretical aspects and required a combination of scientific and also social science methodologies. Accordingly, both the methodology and the validation techniques used pose limitations for this research. The grounded theory section of the methodology occurred in a cyclic fashion that is not typical of scientific research. This occurred because the author was tasked with finding gaps and patterns in a literature search and then in turn the literature was needed to show the gaps and patterns during the content validation. Validation limitations continue into face validity. It can be argued that face validity depends solely on the professionals chosen to validate the research. However, further investigations into face validity shows that a consensus is required for true face validity. Subsequently, the author continuously investigated all deviations from consensus evident in the face validation until consensus was reached. Having realized this limitation, the author will suggest that similar future projects utilize surveys, questionnaires and formal interviews to get quantitative validation results.

5.3 Recommendations for Future Research

This research serves as a foundation upon which future research into tunnelling construction can be built. Accordingly, this research could be developed into a co-production research study (combining industry and academia) of the total risks associated with tunnelling construction. By using conceptual outputs (academia) and incidental outputs (industry) this study could further investigate:

- the importance of risk management throughout the project's life cycle and involve singular investigation into the contractor, designer and other involved parties
- the suitability of technology used for tunnelling construction to determine whether or not they increase the risks on the project
- geotechnical conditions, and
- the level of legislative involvement in tunnelling construction standards and whether more or less would affect risk.

Furthermore, this thesis could lead to the development of an addendum to a contract that includes the mandatory use of a risk register and a checklist for all tunnelling projects. It would also be feasible if a more complete database could be created for public industry use, so that lessons learned and knowledge could be shared openly. A discussion board could be used for open dialog about newly introduced ideas, while a voting system could be created to validate the addition of any new practices to the database.

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