Politecnico di Torino

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Curriculum: Mining Engineering

Master Thesis

Risk Management in Mechanized Tunnelling

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Abstract

This thesis investigates the intricate challenges and risks associated with mechanized tunneling and proposes a comprehensive framework for risk management strategies adaptable to various environments. The study commences with an introduction, providing a background of risk analysis in mechanized excavation and outlining the objectives, scope, and limitations of the study. Research questions and hypotheses are formulated to guide the investigation, followed by a detailed organization of the thesis.

A thorough literature review is conducted to explore risk factors associated with mechanized excavation, the application of risk management in TBM projects, and techniques for risk management. The project development process is examined to understand the various stages involved in mechanized tunneling projects.

Methodology encompasses the research design for risk analysis, numerical/analytical modeling approach for risk analysis, and risk assessment procedures in mechanized tunneling. This includes the identification of hazards in TBM projects and the application of quantitative and qualitative risk analysis methods. Risk management strategies for TBM excavation are developed, focusing on the development of risk mitigation plans and the implementation and monitoring of risk controls.

Specific risks related to shallow conditions and long and deep tunnels are addressed, including risks associated with jamming. Mitigation measures for jamming are explored through the analysis of axial-symmetric FEM, consideration of the time-dependent behavior of the ground, and analytical evaluation.

The thesis concludes with an evaluation of numerical simulation results on risk assessment and a proposal of risk mitigation and control strategies. Recommendations for future research and practical applications are provided.

By adopting a proactive and integrated approach to risk management, tunneling projects can effectively address potential hazards and ensure the safety, resilience, and sustainability of infrastructure and the surrounding environment. This comprehensive framework serves as a valuable resource for stakeholders involved in the planning, design, and execution of mechanized tunneling projects across diverse landscapes.

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1. Introduction

1.1 Background of Risk Analysis in Mechanized Excavation

Tunnel Boring Machines (TBMs) and other cutting-edge technology powering mechanized excavation are transforming the construction of tunnels and subterranean buildings. However, innovation also brings complexity, and project success is inherently risky due to the changing nature of subterranean settings. It is crucial to comprehend the history of risk analysis in mechanized excavation to properly detect, evaluate, and reduce these risks. This succinct overview establishes the groundwork for delving into the historical development and importance of risk analysis techniques within the framework of mechanized excavation. This study intends to offer insights into improving safety, efficiency, and resilience in subterranean construction projects by analyzing the development of risk analysis procedures from conventional methodologies to contemporary strategies specialized for mechanized excavation.

Global urbanization is forcing people to look for sustainable ways to meet the problem of growing mobility in a way that is both environmentally responsible and efficient. Tunnel-based subterranean transit system expansion is one possibility. Reliable information on the anticipated effects of the building method on the built environment is necessary for the stable, affordable, and sustainable design and construction of tunnels. Understanding the dynamic interplay between the tunneling advancement process, the current infrastructure, and the geological conditions is crucial in this regard. Mechanized tunneling is a well-known, adaptable, and cost-effective technique for building subterranean structures. Its expanding application regions and tendency toward bigger shield machine diameters—up to 19.25 meters—are its defining characteristics. (M. Maidl, 2013)

Everyone participating in the project, including those not directly involved, has tunneling, and working underground risks. Any prospective tunnel owner would undoubtedly face significant risks while building a project of this sort due to the very nature of tunnel construction. Ground and groundwater conditions are among the inherent variables that might result in major cost overruns, delays, and environmental degradation hazards. Additionally, there is a chance for significant mishaps when tunneling, as seen by recent dramatic tunnel collapses and other tragedies. Additionally, there is a chance that urban tunnels will cause harm to a variety of unidentified third parties and their property. This is especially concerning in cases where there are heritage-designated structures involved. subsequently, there's a chance that the public unrest brought on by the tunneling project's issues may influence how the project is carried out. (Søren Degn Eskesen, 2004)

1.2 Objectives of the Study

This research has several goals, including exploring the field of automated excavation with Tunnel Boring Machines (TBMs). To begin with, a thorough analysis of the development and status of TBM technology is conducted in order to identify the subtleties and innovations in this field. To give insight on the complexities of TBM technology's evolution, this involves following the technology's path from its conception to its modern uses.

Concurrently, the research aims to examine the geotechnical and risk factors that are specific to TBM excavation, exploring the difficulties and risks associated with automated excavation techniques. This entails a thorough examination of the ground's behavior, geotechnical conditions, and the interactions between different elements that affect the stability and security of excavation projects powered by TBM.

A key aspect of the research involves developing and using numerical models using FLAC 3D, a complex tool that is well-known for its ability to simulate TBM excavation operations. These models are rigorously calibrated and validated, which ensures their precision and dependability and closely aligns their simulations with real-world circumstances.

Moreover, the study aims to evaluate the performance of TBM excavation using comprehensive simulations, offering significant insights into material behaviors and the influence of many elements on the stability and effectiveness of the excavation procedure. Examining simulation findings closely, the research seeks to pinpoint useful risk mitigation approaches that provide doable plans for reducing possible risks and maximizing project benefits.

In the end, by achieving these goals, the research hopes to provide valuable insights that will help shape future developments in the mechanized excavation area and expand our comprehension of TBM excavation techniques. The study aims to improve the effectiveness of risk management techniques in mechanized tunneling projects by clarifying important findings and providing useful suggestions. This will promote safer and more effective excavation operations.

1.3 Scope and Limitations

This study's scope includes a thorough examination of mechanized excavation using Tunnel Boring Machines (TBMs), providing an in-depth look at the state of technology, its historical development, and the geotechnical factors that are specific to TBM use. The use of FLAC 3D numerical modeling to simulate TBM excavation operations is at the heart of this scope, and careful calibration and validation methods are employed to guarantee the correctness and dependability of these models. Simultaneously, the research endeavors to discover and tackle risk factors linked to TBM excavation processes, putting forward efficacious mitigation measures predicated on comprehension gained from simulation outcomes. The study's global reach makes it easier to conduct a comprehensive assessment of international approaches since it covers a wide range of TBM projects from different parts of the world.

It is crucial to recognize the inherent limits of this research, though. A significant constraint is the possible extrapolation of findings from a group of case studies, which could not comprehensively encapsulate the subtleties and intricacies inherent in all TBM initiatives. Furthermore, the study's dependence on easily accessible data could have limitations on the scope and depth of research, especially in situations when complete project data is hard to come by. Furthermore, the breadth of the research may be further constrained by the proprietary nature of some TBM technology and the scarcity of comprehensive project data. Even with our best efforts, it is possible to miss some information on the vast array of TBMs and related projects that exist around the globe.

Additionally, the raw data that accumulates throughout tunneling projects is stored and managed by the data management systems that are now in place. This data is mostly provided as basic text documents, spreadsheets, diagrams, and photos, which makes them challenging to analyze in the absence of a sufficient three- or four-dimensional visualization component. Moreover, a full and all-encompassing perspective of the building processes together with different simulations and measurement data is typically lacking. On the other hand, having a comprehensive and consistent data management plan for the life of a tunneling project is crucial. The aforementioned research studies frequently solely take into account the design or building phases. The raw data that accumulates throughout tunneling projects is stored and managed by the data management systems that are now in place. This data is mostly provided as basic text documents, spreadsheets, diagrams, and photos, which makes them challenging to analyze in the absence of a sufficient three- or four-dimensional visualization component. Moreover, a full and all-encompassing perspective of the building processes together with different simulations and measurement data is typically lacking. On the other hand, having a comprehensive and consistent data management plan for the life of a tunneling project is crucial. The aforementioned research studies frequently solely take into account the design or building phases. (Christian Koch, 2017)

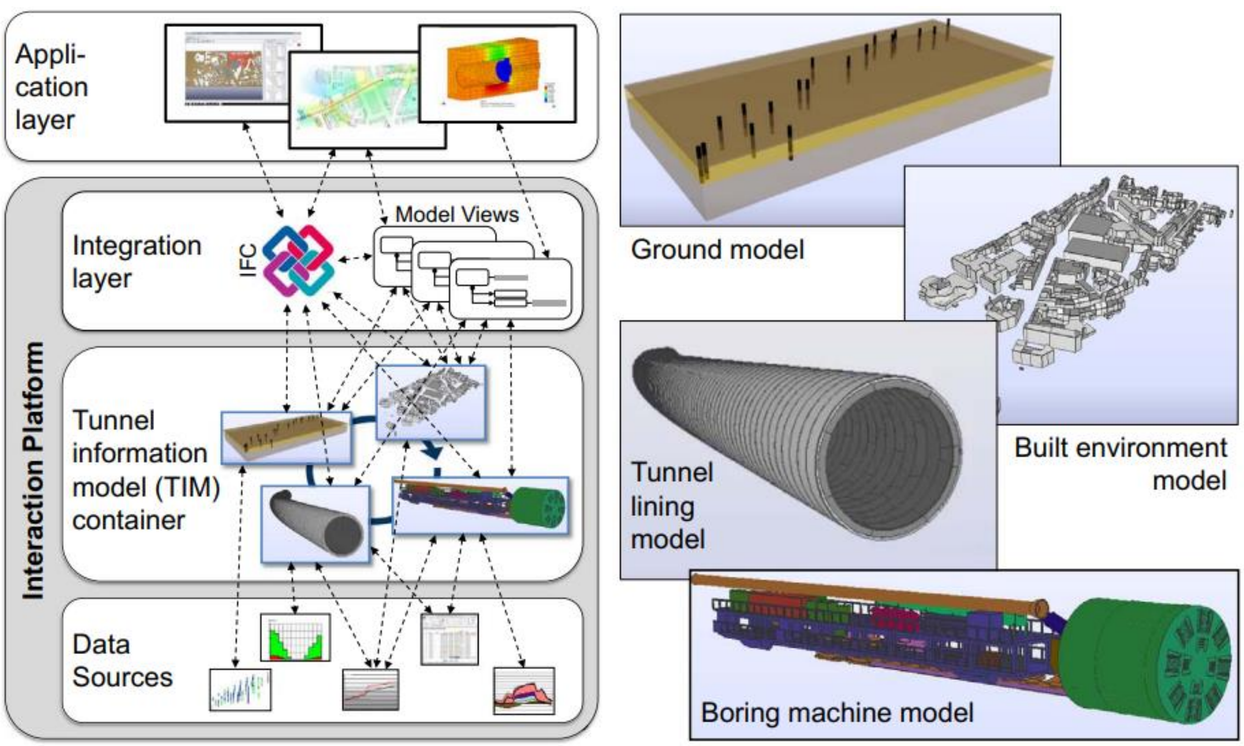

Figure 1. There are four primary subdomain models in the tunnel information modeling framework, which is built on an application layer and a single interaction platform. (Christian Koch, 2017)

It is crucial to recognize and take proactive measures to resolve these constraints in order to maintain transparency and guarantee the validity of the study within the established boundaries. In this manner, the research hopes to preserve objectivity and trustworthiness while offering insightful information on the complexities of TBM excavation and risk management procedures.

1.4 Research Questions and Hypotheses

This study is based on a number of broad research questions and hypotheses that are intended to further our knowledge and progress in the field of tunnel boring machine (TBM)-assisted mechanized excavation. The following important research issues are designed to address important facets of TBM excavation and open the door to significant advances in the field:

Technological Exploits and Historical Developments: Which are the main technological experiments and historical developments in TBM technology, and how have they influenced the development of mechanized excavation as it exists today? Through an examination of the historical development of TBMs, this inquiry seeks to clarify the key developments that have advanced the field.

Geotechnical Difficulties Particular to TBM Diggers: What unique geotechnical problems arise with TBM excavation, and what effects do these problems have on the stability and productivity of the excavation process? This inquiry aims to identify the geotechnical challenges that TBM projects entail and how they affect project performance and safety.

Consequences of Simulation and Effectiveness of Numerical Modeling: How can FLAC 3D be used to successfully model TBM excavation, and what are the consequences of numerical simulations for bettering excavation processes and understanding material behaviors? This topic attempts to clarify the importance of simulation findings in guiding excavation tactics and enhancing project outcomes through thorough numerical modeling.

Control of Surrounding Rock Pressures: What effects do surrounding rock pressures have on the safety and efficiency of tunnel boring machines during excavation, and how may these pressures be successfully handled to guarantee the stability of the tunneling process? This inquiry aims to improve TBM performance in difficult geological circumstances and optimize tunneling operations by analyzing the impact of surrounding rock pressures.

TBM Excavation and Mitigation Strategies' Inherent Risks: What are the dangers that come with TBM excavation, and how may the results of numerical models help design mitigation strategies? This inquiry seeks to improve the safety and resilience of TBM projects by identifying possible hazards and suggesting mitigation solutions.

These research issues will be methodically examined throughout the project to offer thorough understandings of the geotechnical, technological, and risk-aware elements of tunnel boring machine excavation. Furthermore, empirical research carried out within the context of numerical modeling and simulation will verify hypotheses drawn from theoretical frameworks and literature, thus advancing our understanding of this area.

1.5 Organization of the Thesis

This thesis integrates important aspects of technology, geotechnical concerns, numerical modeling, and risk management to give a rational and thorough examination of mechanized excavation using Tunnel Boring Machines (TBMs). The following is an outline of how the thesis is organized:

Chapter 2: Literature Review

This chapter provides a thorough overview of the development of TBM technology over time, highlighting significant breakthroughs as well as recent state-of-the-art discoveries. It examines the unique geotechnical difficulties that come with TBM excavation, giving readers a basis for comprehending the process's dangers. The chapter also examines pertinent research on numerical modeling tools.

Chapter 3: Methodology

This chapter describes the study's research plan and methodology for looking into TBM excavation. It addresses the choice of case studies, techniques for gathering data, and numerical modeling. In addition, the methodology part covers ethical issues in TBM research as well as the calibration and validation of numerical models.

Chapter 4: Risk Assessment and Mitigation Strategies

This part assesses how numerical simulations affect risk assessment in TBM excavation, taking into account the risk elements mentioned in earlier chapters. Based on the results of the simulation, it also suggests practical risk reduction and management measures, highlighting the significance of controlling pressures from nearby rocks.

Chapter 7: Conclusion

The last chapter provides an overview of the main conclusions, knowledge advances, and suggestions for more study and real-world applications. It offers a cogent summary of the study's findings and their consequences for the area of TBM-assisted mechanized excavation.

2. Literature Review

2.1 Risk Factors Associated with Mechanized Excavation

Mechanized excavation poses a variety of risk variables that can affect project outcomes because of its dependence on complicated geological settings and sophisticated technology. These risk variables cover a broad spectrum of difficulties, such as equipment failures, logistical difficulties, environmental concerns, and geotechnical uncertainty. Rockfalls, unstable ground, and water intrusion are examples of geological risks that can seriously jeopardize worker safety and project integrity. Technical issues with TBM operation, including wear on the cutter, malfunctions, and misalignments, can also cause expensive delays and interruptions.

The complexity of subterranean building projects and the possibility of problems interacting with utilities and existing infrastructure further exacerbate the risk environment. To ensure the successful execution of mechanized excavation projects, minimize possible setbacks, and maximize project efficiency and safety, it is imperative to comprehend and properly manage these risk variables. This study attempts to offer insights into creating strong risk management techniques suited to the particular difficulties of mechanized excavation through a thorough review of these risk elements.

Table 1. General Risks within Underground Tunneling (Vittorio Guglielmetti A. M., 2007)

Event Number	Event or Hazard	Background (Main features)	Assessment of the risk		
			Likelihood of occurrence	Consequence or impact	Initial risk
1	TBM	The risk of mechanical or electrical failures of the front and shield sections of a TBM must be considered. Especial attention must be paid to discs in soft or clayey grounds	medium	medium	medium

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		where they cannot properly rotate and tend to wear out or even break. Due to the existence of high clay content usually found in different strata, the probability of these events to take place is between unlikely and likely and the consequence is medium due to difficulty in repairing the discs. That equipment related to safety aspects such as of devices applying counter pressure to the face and keeping it constant with appropriate values, must be double checked and if necessary, the emergency devices must be installed and spare parts on site must be available. The appropriate slurry level and air pressure must be kept constantly carried out by the operator and his assistants with references to technical documents given to them. All the pieces have been checked before its start-up and will be checked again in the chamber after the first run.			
2	Segments grouting system	This point is related to the risk consequent to failures of the grouting system around the mounted ring. The injecting system is managed by an automatic program which also gives information about both the pressure and the quantity of injected mortar per each injector. Risks may be associated	low	low	low

		with the following: 1) mechanical failures 2) lack of power 3) lack or inappropriate mix of mortar supply 4) delays in injection performances 5) inappropriate injection pressure. Delays both in starting and during the performance of injection activity could have negative consequences on the mortar characteristics and on the circuit pipes inside the shield part, whose obstruction could cause serious problems. Improper pressure could cause either incorrect movements of the ring due to injection or insufficient backfilling.			
3	T.B.M. back-up and service equipment installed	The back up is composed of six wagons. Auxiliary equipment installed on it are grease pumping system; segments mortar injection pumping system; main and emergency lighting system; cooling system; secondary ventilation system; stocking area and handling system for mud circuit; cables and utilities reels; ducts and cables waterproofing control; fire protection system; high and low voltage boards; transformer; segments portal crane; segments conveyor belt. Taking into account 1) all the elements that make part of tunnel excavation and lining installation are guaranteed by the relevant supplier; 2)	low	medium	low

		before the start of the machine all relevant tests (single and integrated) shall be performed; 3) daily controls and standard maintenance will be carried out, according to predefined procedures and with clear reference to actions and responsibilities; 4) all the foreseeable spare parts will be available on site, the rating risk would be at low level.			
4	Slurry circuit and muck away system	The system must provide adequate pressure to balance earth and water pressure at the tunnel face. The constraints associated with the production are: TBM advancement rate (amount of soil to be evacuated and then treated), capacity of the treatment unit (slurry production with appropriate density), and pipe diameter (appropriate mucking speed by slurry conveyance ducts). It is foreseen a figure of 900 m3 /h as nominal value for mucking product (excavated soil mixed to slurry) with a value of 1.000 m3 /h as extreme condition. All the operation phases of the slurry circuit are strictly managed by knowing information about the slurry in the feed circuit, slurry in the chamber and finally muck in the return ducts). As a result, the whole system responds to strict control, both	low	medium	low

		automatic and manual, with emergency devices installed on the machinery. It means that any unexpected event that can damage the construction processes is low.			
5	Slurry production and treatment unit	The amount of material to be treated by this unit is 900 m3 /h, but a peak of 1.000 m3 /h must be guaranteed. Due to the external constraints (geometrical, slurry and soil characteristics, TBM advance rate), a margin of approximately 25% at least is then envisaged. Slurry production must be sufficient not to limit the requirements of TBM advance: that is referred of course to all the successive steps in which slurry is involved, from production itself (dry bentonite storage in silos, mixing plant, fresh slurry deposit pools, primary pumps) up to the proper treatment (cyclones and other refreshing equipment) for its recovery; it means to dimension the unit according to peak moments, e.g. with maximum advance rate of the TBM and when mucked soil has the maximum contents of fines. Furthermore, considering that this plant is constituted of two independent units, the excavation progress is anyway granted – even if in reduced speed – also in case of	medium	medium	medium

		damage to part of the treatment plant. Therefore, the only risk is related to the consequences of some failure or incorrect operation.			
6	Human mistakes	A high level of specialization and experience of the personnel represents the main guarantee to limit any kind of operational mistake. The local personnel have been identified through careful selection along the mobilization period. Experience says that mistakes – and sometimes consequent accidents – happen when organization is weak, machinery is obsolete or insufficiently maintained, personnel is tired for hard working conditions and timetables, progress required by a tight planning is overestimated.	low	low	low
7	Lack of resources	The possible lack of resources is attributed to: Personnel; Machinery; Materials (segments accessories, monitoring instruments; Consumables (power, water, and bentonite) and Third Parties (segment manufacturer and specialized companies). It can be said that for each of the situations, likelihood of occurrence could be likely (this is the rating of risk could be assumed between low and medium, detection of its occurrence easy and	high	low	medium

		immediate, definition of mitigation measures almost automatic.			

Number of Event: One

Event/Dangers: Tunnel Boring Machine (TBM)

The front and shield parts of the machine are susceptible to mechanical or electrical failures, which is a danger associated with TBM operations. Discs used in soft or clayey ground conditions should be very carefully considered, as they are more likely to wear out or break and may have trouble turning. The probability of these occurrences transpiring ranges from unlikely to likely due to the high clay content that is prevalent in different layers. Because of the difficulties in either replacing or repairing the disks, the impact of such failures is rated as medium.

Evaluation of the Risk:

Probability of Occurrence: The TBM's medium probability of mechanical or electrical failures is based on the possibility that they may happen, particularly in clayey ground conditions.

Impact or Consequence:

The impact of these failures is likewise rated as medium since it will be challenging to resolve problems pertaining to the front and shield areas of the TBM, especially with regard to disc wear or breaking.

Initial Risk:

Based on the likelihood and impact of the indicated risks, the overall initial risk associated with TBM-related failures is considered medium.

Countermeasures:

In order to reduce the possibility of TBM mechanical or electrical failures:

- Make sure that safety measures on the equipment—like counterpressure devices for the face—are in working order and are inspected on a regular basis.
- When necessary, install emergency equipment, and make sure replacement components are close at hand.
- Throughout operation, continuously maintain the proper air pressure and slurry levels, consulting technical documentation as needed.
- To find any possible problems early on, thoroughly inspect every TBM component before starting it up. After the first operation, do further inspections in the chamber.

Number of Event: Two

Event/Dangers: Grouting system segments

The risk related to the segment grouting system concerns the possible outcomes of grouting process errors surrounding the tunnel boring machine's (TBM) mounted ring. An automated program that tracks the amount and pressure of mortar sprayed into each injector controls the grouting system. Numerous things might cause risks, such as mechanical malfunctions, low power, the wrong mortar mixture, injection performance delays, and the wrong injection pressure. Start or finish times for the injection process might have a negative impact on the properties of the mortar and the integrity of the circuit pipes in the TBM's shield section, which could result in major issues including blockage and incorrect backfilling.

Evaluation of the Risk:

Probability of Occurrence: The automated nature of the injection system and the comparatively low frequency of mechanical faults or power shortages lead to an assessment of a low chance of failures in the grouting system elements.

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Impact or Consequence:

Since there is little direct influence on TBM operations and tunnel construction, the impact of such failures is likewise rated as minor.

Initial Risk:

Considering the possibility and impact of the dangers that have been discovered, the initial risk related to segment grouting system failures is considered to be low overall.

Countermeasures:

To lessen the possibility that the grouting system may fail in segments,

- Establish routine maintenance and inspection programs to quickly detect and resolve any possible mechanical problems or power outages.
- To reduce the possibility of using the wrong mortar mix or injection pressure, make sure the employees using the grouting system have received the necessary training.
- In order to minimize the possible influence on mortar properties and circuit pipe integrity, continuously monitor injection performance in order to identify and rapidly fix any delays.
- Create procedures for modifying injection pressure as necessary to stop the ring from moving incorrectly and guarantee adequate backfilling.

Number of Event: Three

Event/Dangers: Installed TBM backup and maintenance equipment

This point relates to the installed TBM backup and service equipment's risk, which comprises a number of auxiliary systems and parts that are necessary for TBM upkeep and operation. Six wagons make up the backup, each containing auxiliary equipment such as cables and utility reels, fire protection systems, electrical boards, transformers, segments portal cranes, conveyor belts, lighting, cooling, and ventilation systems; stocking areas for mud circuit handling; waterproofing control for ducts and cables; and conveyor belts. The relevant supplier guarantees the availability of all necessary components for tunnel excavation and lining installation, and tests are carried out prior to machine start-up. However, the risk assessment considers the possibility of mechanical failures, power outages, shortages of spare parts, and human error during routine controls and maintenance tasks.

Evaluation of the Risk:

Probability of Occurrence: The assessment of the probability of malfunctions pertaining to the TBM backup and servicing apparatus is minimal, given the thorough testing protocols carried out before to the machine's operation and the presence of pertinent spare parts in the vicinity.

Impact or Consequence:

The impact of these failures is rated as medium since any interruptions to vital machinery may have an effect on TBM operations and cause delays in the tunnel building process.

Initial Risk:

Considering the possibility and impact of the indicated dangers, the initial risk related to malfunctions in the TBM backup and servicing equipment is generally regarded as modest.

Countermeasures:

Measures to Reduce the Risk of Failures in the TBM Service and Backup Equipment:

- Before beginning machine operations, be sure that all systems and equipment have undergone thorough testing in order to find and fix any possible problems.
- Reduce the possibility of equipment breakdowns brought on by human mistake or mechanical problems by implementing routine daily controls and maintenance processes in accordance with established protocols.

- Keep a sufficient number of spare parts on hand to enable quick repairs and replacements as necessary.
- To improve efficiency and lower the chance of mistakes, give staff members in charge of daily maintenance and controls extensive training.

Number of Event: Four

Event/Dangers: Slurry circuit and muck away system

Ensuring sufficient pressure to balance water and earth pressure at the tunnel face during excavation is the primary risk associated with the muck away system and slurry circuit. A few examples of the parameters limiting the system's productivity include the TBM advancement rate, treatment unit capacity, and pipe diameter. For mucking product (excavated dirt combined with slurry), a maximum condition of 1,000 m3/h is specified, with a nominal value of 900 m3/h. Slurry levels in the feed circuit, chamber, and return ducts are continuously monitored as part of the rigorous management of the slurry circuit's operations.

In order to reduce the possibility of unforeseen occurrences interfering with construction operations, emergency mechanisms are fitted on machinery and the entire system is strictly regulated, both manually and automatically.

Evaluation of the Risk:

Probability of Occurrence: The assessment of the probability of unforeseen occurrences impairing the slurry circuit and muck away system is minimal, considering the strict control protocols used and the automation of crucial procedures.

Impact or Consequence:

The impact of such events is rated as medium because delays in tunnel construction may result from disturbances to the slurry circuit, which may affect TBM advancement rates and mucking productivity.

Initial Risk:

Considering the possibility and impact of the dangers that have been identified, the overall risk of the slurry circuit and muck away system being disrupted is considered to be minimal.

Countermeasures:

To lessen the possibility of slurry circuit and muck away system disruptions:

- Install thorough monitoring systems to keep an eye on system performance and slurry levels at all times, allowing for the early identification and handling of possible problems.
- To guarantee optimum performance and avoid mechanical breakdowns, perform routine maintenance and inspections on the system's component parts.
- Employees using the system should receive training to improve their ability to troubleshoot and handle crises.
- To reduce the impact of unforeseen occurrences on construction operations and ensure operational continuity, install redundant systems and backup methods.

Number of Event: Five

Event/Dangers: Slurry production and treatment unit

Ensuring that the slurry production and treatment unit has the capacity to manage the volume of material created during TBM excavation is the main risk involved. With a peak capacity of 1,000 m3/h, the device is made to handle variations in TBM advancement rates and soil properties at a nominal rate of 900 m3/h. To ensure continuous functioning and account for external restrictions, an additional margin of around 25% is incorporated. A number of procedures are involved in the creation and treatment of slurry, such as the storage of dry bentonite, mixing, deposition of the slurry, and treatment with cyclones and other machinery.

The unit is made up of two separate systems that work independently to decrease the possibility of interruptions. This way, in the case of damage or malfunction, excavation can proceed, albeit more slowly.

Evaluation of the Risk:

Probability of Occurrence: Given the intricacy of the system and the possibility of mechanical failures or operational mistakes, the slurry production and treatment unit's risk of malfunctions or improper operations is rated as medium.

Impact or Consequence:

The impact of these failures is likewise rated as medium since they may cause delays in tunnel construction by affecting the efficiency of soil treatment and TBM advancement rates.

Initial Risk:

Considering the possibility and impact of the highlighted risks, the overall initial risk related to malfunctions or improper operations inside the slurry production and treatment unit is classified as medium.

Countermeasures:

To lessen the possibility of delays in the slurry production and treatment unit:

- Establish routine maintenance and inspection plans to quickly detect and resolve any possible operational mistakes or mechanical problems.
- Provide comprehensive training to the staff using the unit to improve their skills and reduce the possibility of mistakes.

- Establish procedures for keeping an eye on system performance and reacting to changes from the intended range of operation.
- In order to ensure operational continuity in the case of breakdowns or malfunctions, install redundant systems and backup procedures.

Number of Event: Six

Event/Dangers: Errors made by people

The risk arising from human error is the possibility of mishaps or errors caused by operational oversights or poor judgment on the part of workers working on tunneling projects. Expertise and experience at a high level among staff members are seen to be the main defense against these kinds of errors. To make sure they have the knowledge and expertise needed for their positions, locally hired staff are carefully chosen and go through mobilization phases. On the other hand, ineffective organizational procedures, antiquated or badly maintained equipment, worker tiredness from hard work and long hours, and unrealistic expectations for advancement can all lead to errors and accidents.

Evaluation of the Risk:

Probability of Occurrence: Given the high degree of specialty and experience among staff members, as well as the stringent selection and training procedures in place, the probability of human error is deemed to be minimal.

Impact or Consequence:

Because experienced workers and well-established safety procedures ensure that human error or accident will not significantly affect tunneling operations, the impact of such mistakes is likewise deemed negligible.

Initial Risk:

Considering the possibility and impact of the dangers that have been discovered, the initial risk related to human error is generally considered to be modest.

Countermeasures:

To lessen the possibility of human error:

- Employees should have access to thorough training and continual professional development opportunities to advance their knowledge and abilities.
- Strict organizational policies and procedures should be put in place to reduce the possibility of mistakes and guarantee effective communication.
- Uphold high standards for machinery and equipment by routinely inspecting, maintaining, and replacing as necessary.
- To avoid mistakes caused by exhaustion, keep an eye on the workload of your staff and give them enough time to recover.
- Set reasonable deadlines and expectations for development in order to save staff from being overworked and to reduce the possibility of overestimation errors.

Number of Event: Seven

Event/Dangers: Insufficient Funds

The risk posed by a lack of resources includes the possibility of a scarcity of labor, equipment, supplies, consumables, and outside assistance needed for tunneling projects. specialist staff, equipment like tunnel boring machines (TBMs), supplies like segments and monitoring equipment, consumables like power, water, and bentonite, assistance from outside vendors, and specialist businesses are examples of resources. The effectiveness and advancement of tunneling operations may be impacted by a scarcity of any one of these resources.

Evaluation of the Risk:

Probability of Occurrence: Due to the wide variety of resources needed for tunneling operations and the possibility of shortages brought on by unforeseen demands or supply chain interruptions, the probability of running out of resources is deemed to be significant.

Impact or Consequence:

The impact of such shortages is assessed as low since, provided mitigation measures are immediately put in place, their immediate influence on tunneling operations may be negligible.

Initial Risk:

Given the possibility and impact of experiencing staff, equipment, supplies, consumables, and outside assistance shortages, the overall initial risk related to a scarcity of resources is rated as medium.

Countermeasures:

To lessen the possibility of a shortage of resources:

- Ensure that you have enough supplies of labor, equipment, materials, and consumables on hand to fulfill project demands.
- To deal with possible shortages quickly, create backup plans and sources of supplies.
- Form alliances and contracts with specialist businesses and outside suppliers to guarantee resource availability and prompt assistance.
- Install monitoring systems to keep tabs on resource usage and spot possible shortages or bottlenecks before they become serious.
- To foresee and prevent any possible deficiencies, conduct routine evaluations and assessments of the needs and resource availability.

By putting these mitigation strategies into practice, the possibility and impact of running out of resources may be efficiently controlled, bringing the total risk down to a manageable level.

It is crucial to use risk management at the outset of a project, when important choices like alignment and building technique selection might have an impact. (Søren Degn Eskesen, 2004)

According to Risk Management Plan (RMP) (Vittorio Guglielmetti P. G., 2008), the following sequential stages are to be followed:

- Identification of risks
- Quantification of risk
- Principal reaction to the hazards that have been discovered (mitigation strategies, such as appropriate design-construction decisions)
- Assessment of remaining risk
- Predetermination of protective actions against lingering hazards

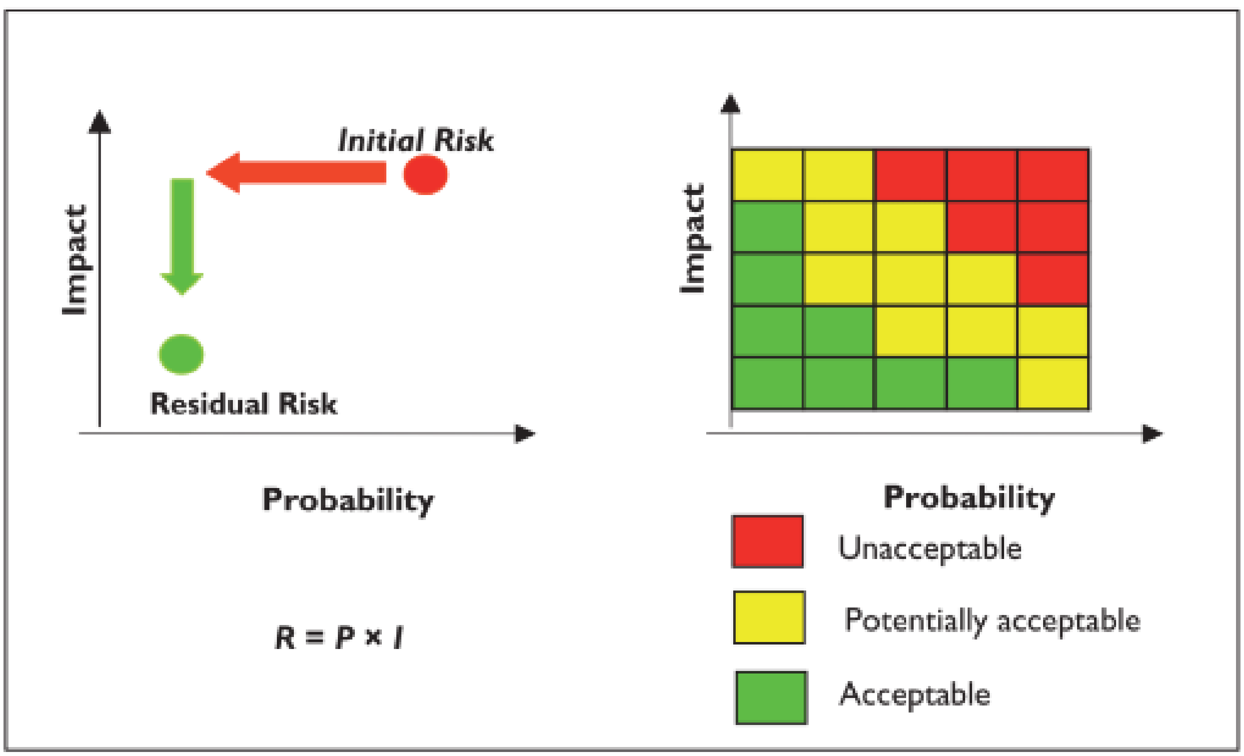


Figure 2. Risk Management Principles (Vittorio Guglielmetti P. G., 2008)

Identification of Risks

There is always a chance of a variety of dangers associated with building projects. An increase in project complexity also increases the project's potential for failure. Based on historical data from tunnel construction, several issues and even tunnel construction failures caused by different causes have been identified, and this can affect how long projects take to complete. It is anticipated that risk management would lessen the negative effects of hazards encountered during building. Identification of hazards that might reduce negative risks is essential for managing high-risk tunnel building projects. It is anticipated that risk management will lessen the negative consequences of hazards encountered during building projects. To handle the hazards we will encounter, risk identification is required. The identification of several risk factors in a project is necessary for the efficient completion of the project in order to successfully increase the performance of tunnel projects. In order to provide a list of the primary risk factors, the research method starts with a thorough literature review that involves reading through at least 48 journals, journal papers, and review articles. This list is then combined with expert knowledge to produce a final risk factor list that includes every risk that could arise during road construction. This research includes identifying and categorizing the different hazards associated with building a tunnel. (Opyn Devinta, 2020)

Choosing the best TBM and estimating its performance in each geotechnical situation are often the most significant issues when mechanized excavation is chosen as the building technique. Because every tunnel is unique and has distinct materials, geologies, habitats, etc., tunnels with diverse constructions may have different flaws. Different flaws might result in various possible failures. (Zhao, 2017) It is feasible to identify the potential location of fractures and the status of lining failure by keeping an eye on internal forces in structures, such as axial force and bending moment. (Qiu, 2020) Even though underground tunnels are often less susceptible than above-ground ones, there is always a chance that they might sustain significant damage that could result in significant losses. (Andreotti, 2019)

Quantification of Risk

Several categorization and rating methods are frequently used to examine this kind of risk. Real risk quantification, however, is also possible and is structured as follows:

To determine the severity of incidence of specific types of failures and to identify the most important reasons, we first employ FTA (Failure Tree Analysis). Second, we use Event Tree Analysis, or ETA, to determine the associated hazards. To get the most precise inputs for analysis, the proposed method assumes information exchange across specific projects. The event and failure trees were created to handle a wide variety of tunnel projects; the inputs will be changed within the specified range in accordance with particular circumstances. It is necessary to first classify the failures based on their nature and effects in order to do the analysis.

As a result, more failure categories were identified:

1. Collapse of a cave-in
2. The tunnel tube's significant deformation exceeded expectations.
3. Beyond the allowable rate of sinking through
4. Disturbance of the surrounding water regime

The fundamental tenet of the classification is the exclusivity of these occurrences/failures, allowing the total risk to be computed as the sum of the risks resulting from specific failures. For example, a significant deformation of the tunnel tube that precedes a cave-in collapse should only be taken into account as a component of the tunnel collapse. (J. Šejnoha, 2009)

Principal Reaction to the Hazards

Prior to starting any tunneling project, geological and geotechnical knowledge is crucial for both excavation and construction. It needs a thorough prediction technique to find possible threats and lower risks. Geotechnical engagement ought to happen all the way through the project. The extent of exploratory research varies according to the project's size and nature. Project-related geotechnical investigation costs might range from 0.1% to 5% of the overall project cost. (Look, 2007) But every mishap that occurs while the project is being built might quadruple its cost. For the tunneling project to be successful, the quality of the inquiry is just as important as its number. The scope of the study will vary depending on the kind of construction, but for tunneling, it should be extended to a depth of up to 3 meters below the invert level or 1 tunnel diameter below the invert, whichever is lower. (Sajjad, 2018)

Since blasting drilling is done throughout each cycle of a mining operation, extended probe drilling is necessary to anticipate additional unanticipated issues and to prevent a potential collapse of the tunnel top. Probe holes (non-core) are often bored in the tunnel's crown. These kinds of holes are utilized to predict rock class, water supply, geological conditions, and rock quality. (Ostberg, 2013)

Construction issues may arise when tunneling through fault zones and poor rock masses, but the chance of failure may be reduced by regularly observing and examining how the support structure and rock mass behave. Important factors include the time of day, the monitoring station's location, and the kind of monitoring system used. Establishing early warning systems against impending earth collapses or damage to structures at the ground's surface may be done with the use of monitoring data. (Kavvadas, 1999)

In conclusion, in order to properly manage risks, a thorough understanding of geological and geotechnical conditions is essential before beginning any tunneling operation. The capacity of geological assessments to forecast future events is critical for spotting possible dangers and reducing risks during the course of the project. Every stage of the project should incorporate geotechnical participation seamlessly, taking into account the size and complexity of the work. The implications of ignoring possible risks during construction can cause project costs to skyrocket, even if the expenses of geotechnical studies may appear insignificant in relation to the total project budget.

The significance of meticulous investigation procedures is underscored by the fact that the quality of geological inquiry is equally important as its depth. Additionally, anticipating construction-related problems is made possible by proactive measures like extended probe drilling and real-time monitoring systems, especially in difficult geological situations like fault zones and weak rock masses. Through the implementation of a proactive strategy for geological and geotechnical risk management, tunneling projects may effectively improve safety, reduce unplanned events, and eventually yield favorable results.

Assessment of Remaining Risk

Subterranean initiatives will inevitably include uncertainty. The root cause of the issue is the inability to fully explore the geological and geotechnical conditions, despite significant preparatory efforts. The accuracy of our predictions of the ground and system behaviors is further reduced by upscaling small-scale laboratory test findings to realistic rock mass volumes and by simplifying our models and analysis.

In line with Eurocode EC 7 (ONORM EN 1997–1), the following important difficulties must be addressed when using the observational approach:

- Establishing safety-relevant factors, such as predicted behavior definitions and standards for evaluating system stability based on anticipated ground conditions.
- The monitoring concept, which takes into account all organizational and technical needs, enables a continual comparison of predicted and observed behavior.
- Concept for managing situations where system behavior and/or ground circumstances differ from expectations, both positively and negatively. (Schubert, 2018)

Predetermination of Protective Actions

Effective risk management in tunnel building projects requires the predetermination of preventive actions in addition to comprehensive geological and geotechnical studies. To make sure that owners and contractors have properly evaluated and managed the risks related to tunneling operations, a detailed checklist and risk register are invaluable resources. These documents serve as proof that, before starting construction operations, common dangers have been properly assessed, handled, and agreed upon.

The research's risk register and checklist give a methodical way to identify and reduce possible dangers, making them useful tools for managing tunneling risks. It's important to understand that although these tools provide a plethora of knowledge on known risks, they are not meant to take the place of common sense or supersede personal judgments. Rather, they ought to be seen as additional resources to help with risk assessment and well-informed decision-making.

It is critical to recognize that not every potential risk may be specifically mentioned in the database or checklist. Nonetheless, these materials may still be extremely helpful as teaching aids, encouraging dialogue, and raising project stakeholders' knowledge of possible hazards. Project teams may improve their preparation and resilience in handling the challenges of tunnel construction by making efficient use of these tools, which will eventually help the project be completed successfully.

2.2 Application of Risk Management in TBM Projects

Early in a project, identifying the risks arising from design and construction is a crucial effort. The owner should create a construction risk policy so that all stakeholders (such as the designers, insurers, contractors, and owners) have a consistent reference. The project's construction risk policy may specify the following: risk objectives, risk management approach, and scope. (Søren Degn Eskesen, 2004)

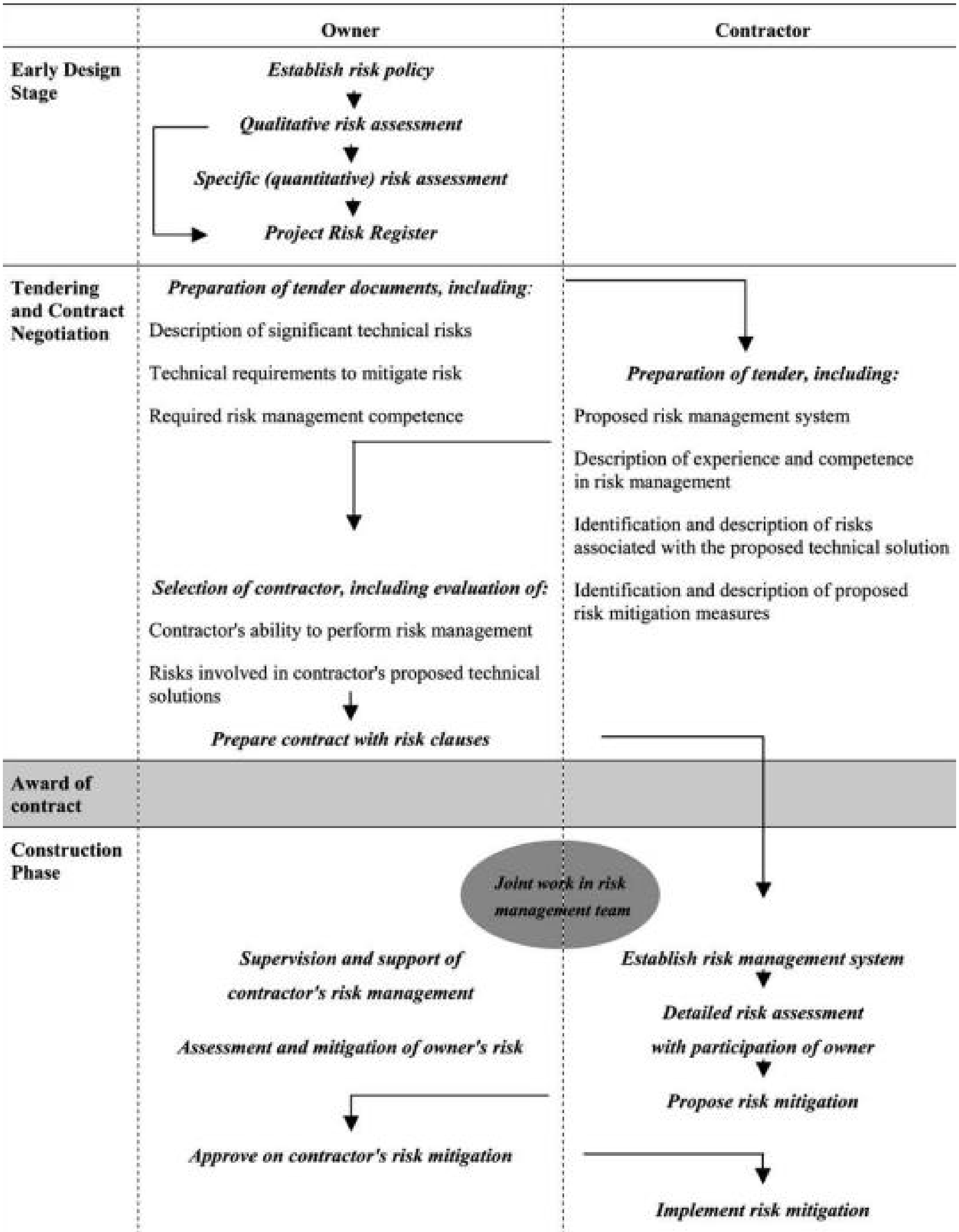


Figure 3. Owner and contractor activity flow for risk management (Søren Degn Eskesen, 2004)

2.3 Technique for Risk Management

The process beginning and the establishment of the setting will build up the structure of risk management, but various parties involved will have varying goals concerning risk assessment. Clients are interested in the purpose of the structure and seek no risk of excess expenses and timing delays. Contractors prioritize output, time and cost considerations, and worker safety. Mainly, risks might be associated with environment, manufacturing, geology, and function. For the purpose of identifying the risk owners, the nature of the contract between the customer and the contractor is crucial. (Stille, 2017)

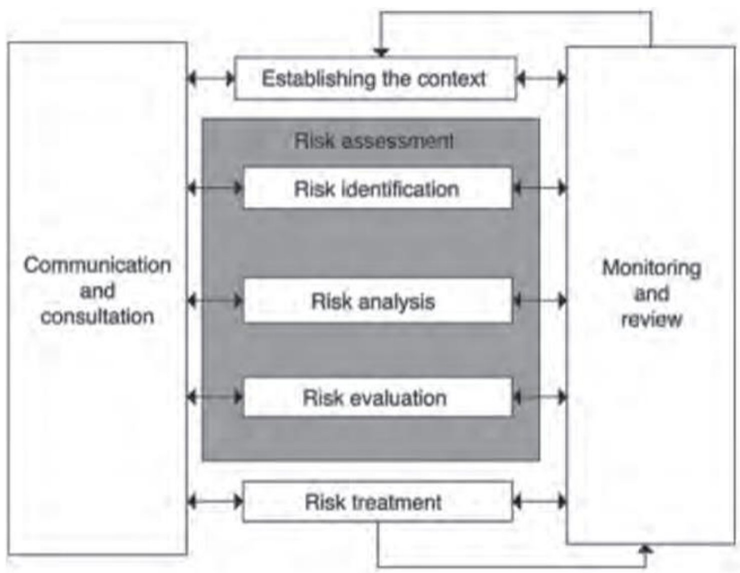


Figure 4. Risk management process (ISO 3100: 2009) (Stille, 2017)

One should implement a risk management plan as part of the construction risk policy. Conducting construction risk assessments according to the information available and the choices to be made or modified at each stage of design and construction is a suggested approach.

Any risk management strategy should contain the following:

- a summary of the actions to be taken at various project stages to meet the objectives.

- a definition of the risk management responsibilities of the various parties involved (different departments within the owner's organization, consultants, contractors)
- a plan for monitoring the outcomes of risk management operations that makes information about hazards (nature and significance) publicly available and in a format that can be shared with all parties; this can be best achieved by creating a thorough risk register.
- monitoring, audit, and review processes.
- original assumptions about the operational phase followed up on.

2.4 Project Development Process

From the beginning to the end, the mechanized excavation project development process is a well-planned trip that guarantees the accomplishment of subterranean building projects. The project's overall vision and objectives, together with site evaluations, stakeholder discussions, and feasibility studies, are set forth at the Project Concept and Definition phase. Subsequently, the Design phase encompasses comprehensive engineering and planning, including geotechnical evaluations, tunnel alignment blueprints, and TBM guidelines. The phase known as "Preparation of Construction," or "Tender Phase," comprises contract discussions, procurement operations, and project agreement finalization. It sets the groundwork for the construction phase to begin. TBMs and related equipment are used throughout the construction phase, with an emphasis on excavation, installing ground support, and implementing quality control procedures.

The Completion/Commissioning phase, which includes testing, commissioning, and delivering the built tunnel to stakeholders, is the last stage of the project. Every stage of the project development process has its own set of tasks, deadlines, and difficulties that must be carefully managed and coordinated in order to accomplish project goals quickly and successfully. Stakeholders may successfully negotiate the complexity and risks associated with mechanized excavation projects by having a thorough grasp of this process, which will eventually lead to safe, sustainable, and successful solutions.

Table 2. General Project Development Phases (ITA, 2016)

General Project Development Phases	Consultant's Tasks	Goal
1. Project Concept and Definition	– Analysis of the needs – Basic Design Criteria Environmental Process	• Purpose of the projects • Design criteria, corridors • Environmental process, approvals and permitting, right of way acquisition
2. Design	– Conceptual (basic) Design – Preliminary Design – Final (detailed) Design	• General layout, feasibility • Cross sections • Detailed design, Construction permit, third party approvals, interfacing design, coordination, and project integration
3. Preparation of the Construction (tender phase)	– Tender Documents – Tender Process	• Draft Contract Documents • Most Economic Offer
4. Construction	– Construction Documents – Site Supervision	• Execution of the work
5. Completion/Commissioning	– Documentation	• As built documentation and

		collecting construction experiences

3. Methodology

3.1 Research Design for Risk Analysis in Mechanized Tunneling

The basis for methodically detecting, evaluating, and minimizing hazards related to subterranean construction projects is laid by the study design for risk analysis in mechanized tunneling. It entails a complex strategy that combines quantitative and qualitative techniques adapted to the particular difficulties encountered in tunneling operations. The selection of suitable risk assessment approaches to thoroughly examine possible risks and their associated probability and effects is one of the key components of the study design. Furthermore, the study design includes the creation of risk registers, stakeholder engagement procedures, and risk management guidelines to support efficient decision-making, communication, and risk management during the course of the project.

Stakeholders may obtain important insights into the intricate risk landscape of mechanized tunneling by utilizing a strong research design. This will allow for proactive risk management techniques, which will eventually improve the efficiency, safety, and success of subterranean construction projects.

Past construction project knowledge on failure events and related variables is seen to be potentially very helpful in risk management. But a number of factors are limiting its broader application. This kind of information is typically hard to come by, rarely recorded, and sometimes even inaccessible when needed. Moreover, there are no tried-and-true techniques for integrating and analyzing it economically. (Ibsen Chivatá Cárdenas, 2013)

To sum up, the risk analysis study design for mechanized tunneling provides a strong basis for methodically identifying, assessing, and reducing the risks associated with underground construction projects. This comprehensive approach combines qualitative and quantitative methods specifically designed to address the special difficulties faced during tunneling operations. The careful selection of risk assessment techniques to fully investigate possible dangers, their likelihood, and their potential effects is essential to the research design.

The research design also includes the creation of risk registers, protocols for engaging stakeholders, and recommendations for risk management in order to support effective decision-making, communication, and risk reduction during the course of the project. Through the deployment of a comprehensive study design, stakeholders may obtain significant insights into the intricate risk environment associated with mechanized tunneling. This will facilitate the proactive risk management strategies that can be employed to augment project efficiency, safety, and success.

It's crucial to recognize the drawbacks of using historical building project information to control risk, though. Even while this kind of information may be valuable, it is sometimes hard to get, inadequately recorded, and unavailable when needed. Moreover, consistent methods for efficiently integrating and economically evaluating this data are lacking. In order to ensure the long-term success and sustainability of underground building projects, it will be imperative to address these problems and advance risk management procedures.

3.2 Numerical Modeling Approach for Risk Analysis

Numerical modeling is an effective tool for risk analysis in the field of mechanized tunneling. It provides information about the intricate relationships that exist between geological conditions, tunneling techniques, and possible risks. A popular numerical modeling program called FLAC 3D offers a flexible platform for modeling how rock masses and tunneling processes behave in different conditions. The process of creating intricate computer models that mimic the geotechnical circumstances and building processes seen in actual tunneling projects is known as numerical modeling. Through the integration of information from site studies, TBM specifications, and ground support systems, these models facilitate the assessment of excavated tunnel stability, the prediction of ground settlement, and the appraisal of risk mitigation strategies' efficacy by engineers.

By using sophisticated analytical techniques like discrete element modeling and finite element analysis, FLAC 3D makes it easier to identify important failure mechanisms and measure the risks that go along with them. Throughout the course of mechanized tunneling projects, utilizing this numerical modeling methodology gives stakeholders the ability to make well-informed decisions, improve construction techniques, and proactively manage risks.

3.3 Risk Assessment Procedures in Mechanized Tunneling

It is essential to start risk management as early as feasible, preferably in the project feasibility and early planning stages, for a tunneling project (or any other kind of construction work) to be effective. The goals of the exercise are established by the owner's risk policy, and while working, all current project team members as well as any new hires should keep the whole risk management process in mind.

It is crucial to remember that the effectiveness and advantages of putting into practice effective risk management depend on the caliber of the risk-mitigating measures that have been identified as well as on the participation, experience, and general consensus of the parties involved (owner, designers, and contractors).

Risk management may be improved through seminars and meetings where awareness and appreciation of the risk management objectives are distributed throughout the organizations. Risk management is not achieved by the implementation of systems and processes alone. (Søren Degn Eskesen, 2004)

3.3.1 Identification of Hazards in TBM Projects

It is important to keep in mind that the quality of the risk-mitigating measures that have been identified, as well as the involvement, experience, and general consensus of the parties involved (owner, designers, and contractors), determine the effectiveness and benefits of implementing effective risk management. By educating employees on the goals of risk management and spreading knowledge of them across the firm, seminars and meetings may help enhance risk management. It takes more than just putting procedures and systems in place to manage risks. (ITA, 2016)

The organization should use risk identification methods and instruments that are appropriate for the threats it faces, its goals, and its capabilities. Finding current and pertinent information is crucial for risk assessment. If at all feasible, this should contain the relevant background data. Those who possess the necessary expertise ought to be involved in risk identification. (ISO, 2009)

3.3.2 Quantitative and Qualitative Risk Analysis Methods

Gaining a knowledge of the risk is a necessary step in risk analysis. Risk analysis is a useful tool for risk assessment, helping determine which hazards require treatment and what kind of therapy is most suitable. When decisions need to be made and there are several possibilities with varying degrees of risk, risk analysis may also be used as a guide. Risk analysis entails taking into account the origins and causes of risk, as well as the possible positive and negative outcomes and their probability of occurring. It is important to determine the factors that influence the likelihood and consequences. Analyzing risk involves figuring out the likelihood of the effects as well as other aspects of the risk. A single incident may impact several goals and have several effects. (ISO, 2009)

Risk assessment procedures, followed by the creation of risk registers, are necessary to determine who is responsible for what risks and to provide a clear and succinct description of how those risks will be assigned, controlled, mitigated, and managed. The risk tracking systems should make it possible to manage and mitigate risks by putting controls and backup plans in place that can be monitored at every step of a project. (ITIG, 2006)

3.4 Risk Management Strategies for TBM Excavation

In order to minimize the risks and uncertainties that come with tunnel boring machine (TBM) excavation projects, effective risk management is essential. Throughout the course of a project, proactive steps are taken to detect, evaluate, and control risks as part of a complete risk management plan. Early detection of possible risks, such as environmental variables, equipment failures, and geotechnical instability, is a crucial component. A methodical approach to risk identification is made easier by the use of instruments like hazard analyses and risk registers. Consequently, stakeholders can rank risks according to likelihood and possible effect by using risk assessment approaches including qualitative and quantitative analysis.

Equipped with this knowledge, customized risk reduction strategies—which may include operating procedures, engineering controls, and backup plans—can be formulated and executed. The implementation of routine monitoring and evaluation procedures guarantees the efficacy of these measures and allows prompt modifications in response to changing project circumstances. Additionally, encouraging a collaborative and safe culture within project teams raises risk awareness and encourages proactive risk management practices. In TBM excavation projects, stakeholders may reduce project interruptions, protect worker safety, and maximize project outcomes by adopting strong risk management measures.

3.4.1 Development of Risk Mitigation Plans

When choosing the best risk treatment solution, one must weigh the advantages against the costs and implementation difficulties, taking into account legal, regulatory, and other obligations including social responsibility and environmental preservation. hazards that may require risk treatment but are not economically justified, such as severe (high negative consequence) but uncommon (low chance) hazards, should also be considered in decision-making. (ISO, 2009)

The optimal risk treatment option should be selected after weighing the benefits against the costs and implementation challenges. Other considerations that should be made include social responsibility and environmental preservation in addition to legal and regulatory requirements. Decision-makers should also take into account risks that would need risk treatment but are not economically justifiable, such as severe (high negative consequence) but unusual (low likelihood) hazards. (ITA, 2016)

3.4.2 Implementation and Monitoring of Risk Controls

Regular checking or surveillance should be a component of both the monitoring and review phases of the risk management process. It might be sporadic or regular. Clear definitions of monitoring and review responsibilities are necessary. All facets of the risk management process should be covered by the organization's monitoring and review procedures in order to:

- guarantee that controls are efficient and effective in their design and operation.
- gather additional data to enhance risk assessment.

- analyze and draw conclusions from events (including near-misses), changes, trends, successes, and failures.
- detect changes in the internal and external context, including adjustments to risk criteria and the risk itself, which may necessitate adjusting risk treatments and priorities.
- identify emerging risks.

As applicable, the outcomes of the monitoring and review process should be documented, communicated both internally and externally, and utilized as a starting point for the evaluation of the risk management framework. (ISO, 2009)

3.5 Risk for Shallow Conditions

The quality of the rock mass, the existence of rock joints and their geometrical characteristics, the in-situ stress ratio, the depth below the surface, and the geometry of the apertures are some of the critical criteria that determine how serviceable an underground entrance is. (Wael R. Abdellah, 2018)

When it comes to buildings in cities, mechanical tunneling affects not just the buildings right next to work sites but also ones a few blocks away. Ground settlement, which results from soil compaction and displacement during excavation, is one of the main issues related to tunneling operations. The diameter and depth of the tunnel, the state of the soil, and the distance between nearby structures and the construction site are some of the variables that affect how much earth settles. Structures that are close to tunneling activities are especially susceptible to harm from settling since even little movements in the earth can result in large structural deformation.

Vibrations produced by tunnel boring machines (TBMs) as they descend down spread across the nearby rock and soil. These vibrations have the ability to intensify their impacts and perhaps cause structural resonance and damage by resonating with the natural frequencies of adjacent buildings. In addition, the noise produced by tunneling operations can interfere with residents' everyday routines, alter their sleep cycles, and lower their standard of living in general. Urban dwellers and workers who are exposed to excessive noise and vibration levels over an extended period of time may experience stress, discomfort, and even health problems.

Dewatering operations are also frequently used during tunnel construction to regulate groundwater levels and avoid floods in the excavation region. Dewatering, however, has the potential to modify subsurface hydrology, which might impact groundwater levels and flow patterns. Groundwater level variations may impact the integrity of foundations and raise the danger of subsidence in buildings near tunneling operations, especially in places with shallow water tables or unstable soils.

In addition, subterranean services like gas, water, and phone lines might be damaged by the excavation and building processes involved in tunneling operations. Unintentional harm to these utilities may cause service interruptions, which might put building occupants' safety and comfort at risk. Furthermore, excavation close to existing structures may be necessary for the relocation or protection of utilities, raising the risk of damage to structural components and foundations.

Comprehensive monitoring methods are frequently put in place to detect ground movements, vibration levels, and noise emissions during tunneling operations in order to reduce these dangers. In order to prevent damage caused by settling, building owners and developers may also use structural reinforcing techniques like bracing or underpinning. Effective implementation of mitigation measures and minimization of possible impacts on buildings in urban locations necessitate collaboration among tunneling contractors, engineers, and building owners.

Ground Settlement

Mechanized tunneling excavation operations may result in ground settlement, which might endanger neighboring structures. Excessive settlement can jeopardize a building's stability and safety by causing structural damage such as foundation movement, wall or floor fissures, and structural element misalignment.

Noise and Vibration

Mechanized tunneling activities produce a great deal of noise and vibration, which can reverberate through the earth and have an impact on structures close by. Building materials may get fatigued from prolonged vibration exposure, which might result in degradation and structural damage. Furthermore, loud noises can lower the standard of living in cities, interfere with daily activities, and disturb residents' comfort.

Groundwater Infiltration

Digging tunnels may cause disturbances to subterranean waterways and aquifers, which might result in groundwater infiltration and possible basement or lower-level flooding in structures. Water intrusion can endanger the safety and health of building inhabitants by destroying interior finishes, electrical systems, and foundations.

Cracks Caused by Construction

Excavation and construction work for tunnels can cause stress redistribution and ground movement, which can lead to the development of cracks in nearby buildings. These construction-related fissures have the potential to weaken a building's structural integrity by permitting insects, moisture, and air intrusion. This might raise maintenance expenses and lower the value of the property.

Utility Disruption

When performing mechanized tunneling operations, subterranean utilities including electricity conduits, sewage lines, and water pipelines may need to be moved or protected. Unintentional damage to utilities during tunnel construction can cause buildings' vital services to be interrupted, causing resident discomfort as well as possible safety risks.

Vehicles and Accessibility

Road closures, detours for vehicles, and modifications to pedestrian access routes are common during tunnel construction activities. These measures can cause disruptions to regular business operations and have an impact on how accessible buildings are. Building owners and tenants may face financial risks as a result of reduced accessibility, which may affect foot traffic, customer access, and revenue production for companies.

These six issues cover a wide range of difficulties that mechanized tunneling projects in urban environments can provide, each having unique consequences for the built environment and its occupants.

3.5.1 BCS + BRA

Building Condition Survey (BCS)

Proactive building management includes the Building Condition Survey (BCS) and Building Risk Assessment (BRA), which are essential tools for assessing the structural soundness, functioning, and safety of existing buildings. The Building Condition Survey (BCS) entails a thorough examination and evaluation of a building's exterior, including its structural components, mechanical and electrical systems, interior finishes, and building envelope. The BCS attempts to find any flaws, degradation, or other risks that can jeopardize the building's performance or safety through visual inspections, testing, and analysis.

The BRA expands the examination after the BCS in order to investigate any possible dangers related to the detected building problems. It entails using the BCS results to analyze the possibility and effects of a variety of risks, including structural instability, fire dangers, water intrusion, and environmental threats. To assess the degree of risk associated with each recognized hazard, the BRA takes into account variables including occupancy, building use, geographic location, and regulatory requirements.

When combined, the BCS and BRA offer insightful information on the general health and safety of buildings, assisting stakeholders in creating plans for risk mitigation, maintenance, and repair that are suitable. Stakeholders may prioritize investments, distribute resources efficiently, and guarantee the durability and resilience of the built environment by methodically evaluating building conditions and threats. Furthermore, proactive monitoring of building conditions over time is made possible by routine BCS and BRA updates, which also minimize potential liabilities or interruptions related to building failures or safety events. In the end, the BRA and BCS are crucial instruments for advancing sustainable building management techniques, occupant well-being, and building safety.

The two main groups of activities that make up the process of evaluating the risk of damage for buildings that may be impacted by tunnelling-induced settlements are: (a) the Building Condition Survey (BCS), which verifies the actual state of buildings before, during, and after tunnel construction; and (b) the Building Risk Assessment (BRA), which calculates the potentially expected damages based on settlement predictions and the intrinsic vulnerability of the structures.

The overall procedure comprises the following anticipated steps:

- Determine the "control parameters," or the variables that affect how a building reacts to settlements.
- Based on the values anticipated by the "control parameters," ascertain the general standards for establishing limitations for the settlement and heave as functions of the particular damage classification system used for the project.
- Undertake the general ground movement prediction (greenfield movements) in order to identify the "construction zone of influence" (also known as the "control zone"), within which buildings must be inspected to assess the risk of damage (e.g., all buildings within the contours of 1/750 angular distortion and 5 mm settlement, or all buildings at a specific distance on each side of the tunnel alignment).
- For every building that has been identified as being within the "control zone," conduct a settlement-sensitivity analysis (i.e., evaluate each building's condition in relation to the amount of ground movement it can withstand before any visible damage begins to appear) and establish the tolerance levels for the maximum amounts of settlement, angular distortion, or deformations.
- Sort all the detected buildings into various risk groups by comparing the settlement forecasts with the settlement-sensitivity analysis's findings.
- In order to record the anticipated ground movements and the reaction of nearby buildings and services, prepare a Ground Movement Analysis Report taking into account the following factors: the ground conditions, the structure's arrangement, the kind of nearby structures and utilities, and the construction process.
- Identify the buildings that need to be protected and that are at risk.
- Determine which structures need to be surveyed and given extra attention while they are being built.
- Specify the approach for managing settlement risk.
- Store and preserve all pertinent building data for usage by all stakeholders in a dynamic, relational GIS database. (Vittorio Guglielmetti A. M., 2007)

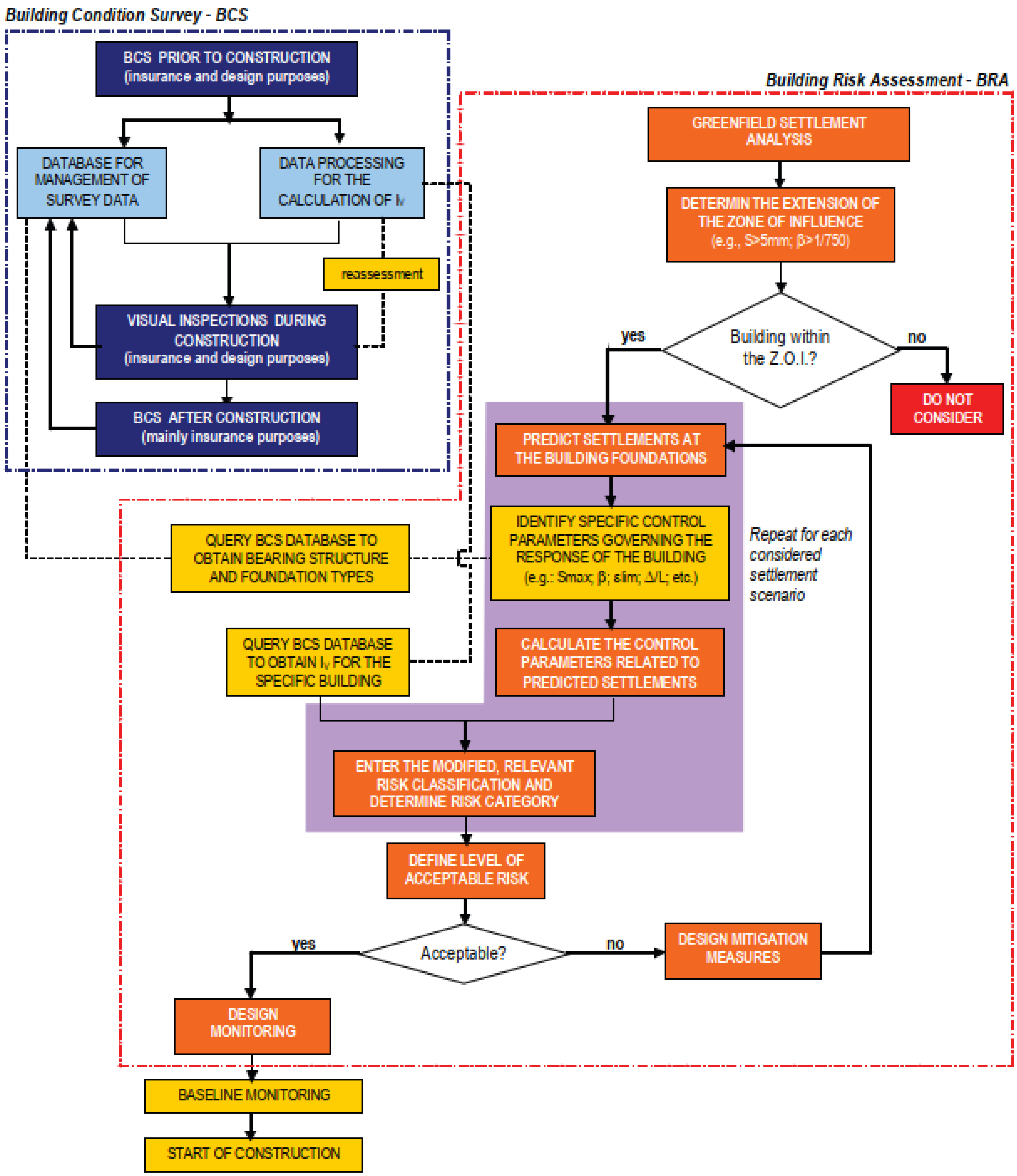


Figure 5. Schematic Flowchart of BCS and BRA (Vittorio Guglielmetti P. G., 2008)

Building Conditions Survey (BCS)

Three separate stages of surveys to map defects—prior to construction, during construction, and post-construction—must be included in the condition surveying of all structures and certain inspectable utilities inside the zone of impact of the subterranean construction activities. Regardless of whether damage is anticipated or has already happened, it is best practice to document the state of every structure inside the control zone for the benefit of all parties concerned.

Furthermore, managing an accurate Building Condition Survey (BCS) is crucial for addressing various possible claims brought forth by property owners. BCS entails gathering historical building data and creating a map of building flaws that will be used to gauge the structure's susceptibility before it is constructed.

A team of qualified structural engineers who will carry out the work on site should create specifications and methods for the BCS surveys, as well as forms for the organized, consistent, and coherent collecting of data. Every building will have its own reference number. This is essential for managing and disseminating information about every property. (Vittorio Guglielmetti P. G., 2008)

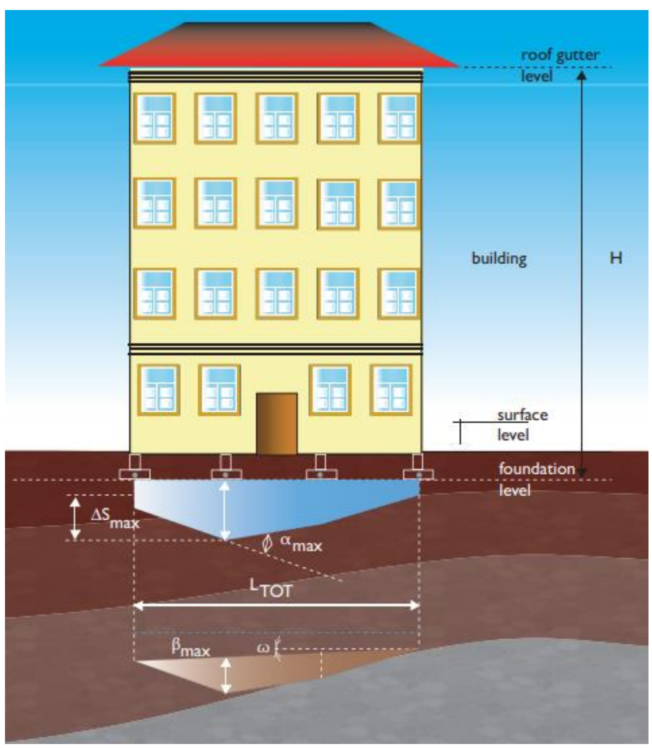


Figure 6. Control parameters that regulate the behavior of a building towards settlements (Burland, 1997)

Table 3. *Example of Calculation of Vulnerability Index (Vittorio Guglielmetti P. G., 2008)*

PROJECT NAME			Building code	PAGE
CALCULATION OF THE VULNERABILITY INDEX Chiriotti et al., 2001)			**0001**	1/2
A. STRUCTURAL BEHAVIOUR OF THE BUILDING (Maxium value: 25)				
Characteristic	***Index***		***Assumed value***	
A.1. Horizontal structural elements				
A.1.1. Wood structure	6		6	x
A.1.2. Reinfor ced concrete	0			
A.1.3. Mixed structure	3			
A.2. Vertical structural elements				
A.2.1. Masonry elements	6		6	x
A.2.2. Steel elements	0			
A.2.3. Reinforced concrete elements	3			
A.2.4. Mixed elements	4			
A.3. Foundations - source of information				
A.3.1. Direct (drawings, contractor)	0			
A.3.2. Indirect (property owner, inhabitants, for similarity with known structures, assessed)	4		4	x
A.4. Type of refurbishment, if any				
A.4.1. Unknown	2			
A.4.2. Increasing opening in the façade (or bearing walls)	6			
A.4.3. Modifications maintaining the construction method	0			
A.4.4. Modifications improving the construction method	3			
A.4.5. Consolidation (bearing structure or foundations)		5		
A.4.6. Adding floors	4		4	x
A.4.7. Small interior works	0			
State of the refurbishment works (*)				
A.4.a. Done or in progress	1	0	x	
A.4.b. Designed	0	1		
A.5. Presence of basement levels				
A.5.1. No	0			
A.5.2. Yes	3		3	x
			PARTIAL TOTAL A.	**23**

Building Risk Assessment (BRA)

The systematic process of detecting, assessing, and managing hazards related to buildings and their inhabitants is known as building risk assessment, or BRA. To determine the total amount of risk that a building poses, a thorough examination of all possible risks, weaknesses, and outcomes is required. Numerous elements are taken into account by BRA, such as occupant behavior, environmental dangers, fire safety, structural integrity, and security issues.

A comprehensive examination and assessment of the building's physical state, including its structural elements, building systems, and safety measures, usually precedes the BRA process. Visual examinations, testing, and analysis may be necessary to find any flaws or possible risks that might endanger the safety of the inhabitants or property.

Following the identification of risks and vulnerabilities, each risk scenario's likelihood and possible outcomes are evaluated as part of the BRA process. This entails taking into account elements including the likelihood of an incident happening, the seriousness of any possible injury, and the efficiency of current mitigation strategies.

Recommendations and methods for risk mitigation are created based on the results of the risk assessment in order to address identified hazards and improve the building's overall resilience and safety. This might entail putting in place security measures, upgrading fire safety systems, upgrading emergency evacuation protocols, or undertaking structural changes.

In particular, given building conditions, occupancy patterns, and external variables may vary over time, it is imperative that the BRA be reviewed and updated on a regular basis to guarantee that risks are adequately managed and mitigated.

In general, building risk assessment, or BRA, is essential to enhance a structure's security, safety, and resilience by shielding its people, possessions, and the neighborhood from possible injury or loss.

It is important to specify the many kinds of damage that a structure can sustain in order to provide a precise damage categorization for buildings. The following are the three commonly used damage classifications:

- Aesthetic problems mostly impact the inside walls and their finishes and are associated with minor structural cracks. Damage to appearance is easily fixed; usually, a simple redesign will hide the light cracks.
- Functional damages refer to the loss of use or functionality of building components (such as stuck doors and windows and damaged pipelines) or of delicate equipment inside the building (like precision instruments that are sensitive to differential movements); the building's structural integrity is unaffected; however, the building's and its tenants' commercial and economic prospects may suffer.
- Damage to the structure that results from severe deformations or cracks in the supporting structures might cause the building to collapse completely or partially. Underneath the coatings, structural

deterioration may occasionally stay partially undetected. Nonetheless, plaster and whitewash are reliable markers of the spread of cracks.

The damage classifications found in technical literature are based on the kind of damage as well as the range of values that specific control parameters assume as a result of movements that external sources (such tunneling) produce in structures. Different control parameters are used by damage classifications based on the particular types of structures they pertain to.

Table 4. Damage classification (Burland, 1997)

Category of risk of damage	*Degree of severity*	*Description of typical damage*	*Crack width [mm]*	*Control parameter (tensile strain) ε_{lim} [%]*
0 aesthetic	Negligible	Hairline cracks	<0.1	0–0.05
1 aesthetic	Very slight	Fine cracks which are easily treated during normal decoration. Damage generally restricted to internal wall finishes. Close inspection may reveal some cracks in external brickwork or masonry.	<1.0	0.05–0.075
2 aesthetic	Slight	Cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings. Cracks can be visible externally and some repointing may be required to ensure watertightness. Doors and windows may stick slightly.	<5.0	0.075–0.15
3 aesthetic/ functional	Moderate	The cracks require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Watertightness often impaired.	5–15 (many crack with width >3 mm)	0.15– 0.3
4 functional/ serviceability	Severe	Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some lose of bearing in beams. Service pipes disrupted.	15–25 (but depend on the number of cracks)	>0.3
5 structural	Very severe	Major repair job involving partial or complete rebuilding. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability.	>25 (but depend on the number of cracks)	

When "hogging mode" induced deformations occur in bearing structures in masonry and framed buildings, it suggests a situation in which the middle portion of the structure deforms upward, and the ends deform downward. Numerous reasons, including unequal loads, foundation movement, or structural instability, might lead to this style of deformation.

The likely behavior during hogging mode deformations in masonry buildings—which usually have load-bearing walls and arches—depends on the building materials, bond patterns, and overall structural arrangement. Under such circumstances, the extremities of load-bearing walls may suffer compressive pressures that might cause crushing or buckling, while the midsection may experience tensile stresses that could cause cracking or bulging. Arches may also behave differently, with compressive loads acting on the extrados (outer curve) and tensile stresses acting on the intrados (inner curve). Masonry structures experiencing hogging mode deformations may show localized damage, such as fractures or displacements, if they are not sufficiently reinforced or supported. This might jeopardize the stability and load-bearing capability of the structures.

The way that structural frames made up of beams and columns respond to deformations caused by the hogging mode varies depending on the member characteristics and framing technique used in framed buildings. A hogging mode situation causes beams to deflect upward in the middle and downward at the ends due to tensile loads along the higher fibers and compressive pressures along the lower fibers. Similar to this, columns can experience tension at their lower parts and compression at their upper parts, which can influence their stability and ability to support loads. Framed structures experiencing hogging mode deformations may show excessive deflections, localized collapses at connections, or even global collapse under extreme loading circumstances if they are not adequately constructed or reinforced.

In general, the behavior of bearing structures in masonry and framed buildings subjected to hogging mode deformations is likely to occur, which emphasizes the significance of conducting structural analyses, designing properly, and maintaining them to guarantee their stability, integrity, and safety against possible structural hazards or failures. Furthermore, prompt intervention and structural strengthening can be required to reduce hazards and maintain the structural integrity of structures that experience these kinds of deformations.

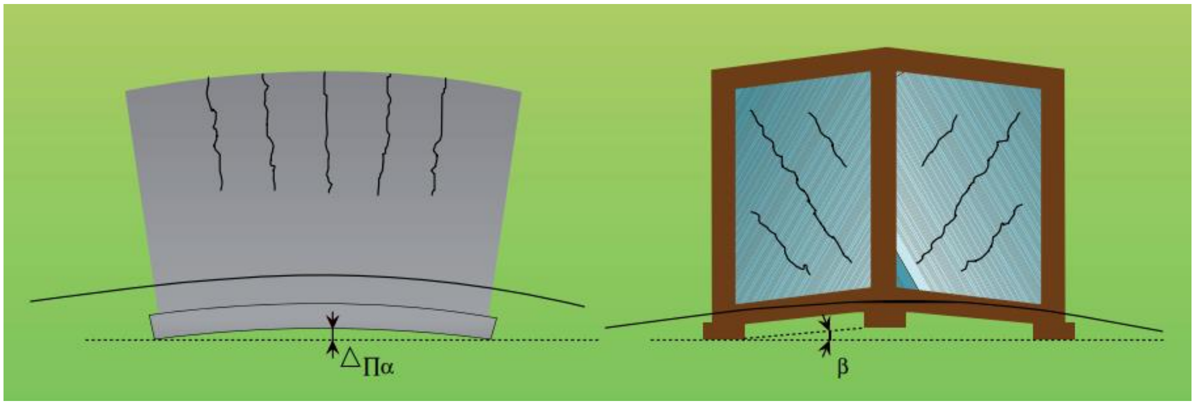


Figure 7. Probable behavior of different kind of bearing structures undergoing a "hogging mode" type of induced deformations in masonry and framed buildings. (Vittorio Guglielmetti P. G., 2008)

According to Vittorio Guglielmetti P.G.'s 2008 description, the calculation sections for structures inside the control zone usually entail evaluating the structural reaction of buildings to varied loading circumstances, including seismic occurrences. The purpose of these computations is to ascertain the building's seismic force resistance and guarantee the security of its residents and surrounding buildings. An outline of the typical computation parts is provided below:

Analyzing Structure

A thorough assessment is carried out as part of the structural analysis process to determine how the building reacts to different kinds of loads, such as dead loads, living loads, and external loads like wind. The goal of the static analysis, which includes this evaluation, is to comprehend the behavior of the structure under various loading scenarios.

The term "dead loads" describes the constant or static forces that a building experiences as a result of its own weight as well as the weight of its structural parts, walls, floors, and roofs. These loads are often predictable and stay consistent over time depending on the materials and structural design. Engineers use static analysis to determine how dead loads are distributed across a structure and make sure it can safely sustain its own weight without undergoing significant deformation or failing structurally.

On the other hand, living loads are dynamic or changeable forces that the building's inhabitants, furnishings, equipment, and other mobile items place on the structure. The building's function, occupancy, and usage patterns can all affect these loads, which can change over time in terms of intensity and distribution. In order to estimate and evaluate the effect of living loads on the stability and performance of the building, engineers use static analysis, taking into account variables like occupancy levels, furniture configurations, and expected activities.

External loads are forces from the surrounding environment acting on the structure, such as wind, earthquake, and thermal loads. For instance, wind loads, which are determined by variables like wind speed, building height, and orientation, are the force that the wind applies to the surfaces of the structure and can change in both direction and amplitude. Evaluating how these external loads affect the structure's response—that is, its capacity to withstand lateral forces, preserve structural integrity, and guarantee occupant safety—is known as static analysis.

Through the methodical examination of the structure's response to external loads such as wind, dead loads, and live loads using static analysis, engineers may get important insights about the structural behavior and performance of the building. With this understanding, they can design structures that are durable and structurally sound, able to endure a wide range of frequently unanticipated pressures.

Dynamic Analysis

In structural engineering, dynamic analysis is a vital technique used to assess how structures behave under seismic pressures and to get important insights into how they react to seismic occurrences. This analytical method is especially important in earthquake-prone areas where structures have to be built to resist the potentially catastrophic consequences of ground motion. In dynamic analysis, a number of methods are frequently applied, such as time history analysis, response spectrum analysis, and modal analysis. Every technique has unique benefits and is chosen according to the building's characteristics and the level of seismic risk.

A key element of dynamic analysis is modal analysis, which focuses on the inherent frequencies and mode shapes of the structural system of the structure. Engineers can evaluate the dynamic properties of a building and its probable sensitivity to resonance during seismic occurrences by determining the prevalent vibration modes. For the purpose of creating suitable dampening systems and maximizing the building's reaction to seismic forces, this knowledge is crucial.

Another popular technique in dynamic analysis is response spectrum analysis, which provides a straightforward yet efficient way to assess the seismic performance of the building. Using this technique, the structure is subjected to a range of ground motion recordings that correspond to varying seismic intensity levels. The building's reaction to peak displacements, accelerations, and forces is then evaluated by engineers, enabling the calculation of seismic demands and the design of appropriate structural components and systems to withstand these forces.

The most thorough and in-depth technique for dynamic analysis is time history analysis, which simulates real ground motion data over time. This method takes into consideration the dynamic interplay between the ground motion and the building, taking into account the intricate and nonlinear behavior of the seismic forces as well as the structure. Time history analysis gives engineers detailed information on how a structure will behave during particular seismic occurrences, allowing them to evaluate performance standards including displacement, acceleration, and interstory drift.

In general, dynamic analysis is essential to the seismic design of buildings because it aids engineers in determining the stability, resilience, and structural integrity of buildings under seismic loads. In seismically vulnerable areas, engineers may create strong, earthquake-resistant designs that put occupant safety and structural durability first by using modal analysis, response spectrum analysis, or time history analysis.

Design Points to Remember

To guarantee the resilience and safety of structures designed to withstand seismic pressures, a number of important factors need to be taken into account. Developing sturdy, earthquake-resistant structures that can withstand the dynamic stresses exerted during seismic occurrences requires careful consideration of these design factors.

Establishing the seismic design criteria unique to the project area is first and foremost important. This involves figuring out the region's seismic hazard levels, which are usually established by taking into account elements like the area's proximity to active fault lines, past seismic activity, and geological features. Comprehending the magnitude of seismic risk enables engineers to evaluate possible hazards and develop structural plans appropriately.

Characterizing the specific ground motion features of the project location is also crucial. The movement of the earth's surface during an earthquake is referred to as "ground motion," and it can vary greatly based on a number of variables, including the kind of soil, the geology of the site, and the distance from the seismic source. Engineers can successfully adapt the structural design to handle the predicted seismic stresses by studying the site-specific ground motion data. Adhering to the seismic design specifications specified in building codes or standards that are relevant to the project site is also crucial. These rules usually include minimal standards for design, performance goals, and building techniques that are intended to guarantee the structural soundness and security of structures in the event of an earthquake. By adhering to these recommendations, engineers may create structures that adequately safeguard people and property while meeting or beyond the required seismic resistance criteria.

In conclusion, it is critical to define the seismic design parameters, describe the site-specific ground motion characteristics, and follow the seismic design specifications specified in building codes or standards when constructing buildings to withstand seismic forces. Engineers may create strong, earthquake-resistant designs that put occupant safety and structure durability first in seismically active areas by carefully taking these aspects into account.

Structural Configuration

To guarantee a building's stability and resistance to seismic forces, a number of important considerations must be made while analyzing its structural arrangement for seismic design. The layout and geometry of the construction, which comprises the general shape, size, and placement of building parts, is one of the main factors to be taken into account.

The building's seismic performance is mostly determined by the structural system that was selected, whether it is made of steel, masonry, or reinforced concrete. Regarding strength, ductility, and stiffness, each structural material has certain benefits and drawbacks that should be carefully considered in light of the project specifications and site circumstances. For instance, reinforced concrete structures are quite strong and long-lasting, yet they could need further reinforcing to properly withstand seismic pressures.

The arrangement of the structural system itself is crucial, in addition to the selection of the structural material. This covers how the building's walls, columns, beams, and other load-bearing components are arranged. In order to effectively transport seismic pressures from the roof to the base and through lateral load-resisting systems like shear walls or moment frames, the structural system must be constructed.

To make sure that seismic stresses are dispersed equally and safely throughout the building, it is crucial to evaluate the load routes inside the structure. This entails examining the loads that are moved from the higher stories to the base and locating any possible weak spots or load route discontinuities that can jeopardize the structural integrity of the structure in the case of a seismic event.

In addition, lateral load-resisting components like moment frames, braced frames, and shear walls must be carefully chosen and positioned in order to absorb seismic energy, dissipate it, and avoid excessive deformation or collapse. These components need to be placed carefully and constructed appropriately to have enough stiffness and strength to withstand the lateral forces produced by seismic disturbances.

Engineers are able to design structures that are robust and able to endure seismic forces by carefully analyzing the building's geometry, layout, and structural system; they can also evaluate load routes and install suitable lateral load-resisting systems. In earthquake-prone areas, this comprehensive approach to structural design is crucial for guaranteeing the stability and safety of structures.

Building Response

A crucial first step in evaluating the structural response of structures to seismic pressures in seismic engineering is estimating the base shear. The whole lateral force applied to the building's foundation as a result of seismic motion during an earthquake is represented by the base shear. Because it directly affects the design of lateral load-resisting parts and the overall structural performance, it is a crucial parameter in the design of earthquake-resistant structures.

The mass of the building, seismic design requirements, and the outcomes of dynamic analysis are some of the variables that must be taken into account in order to determine the base shear. One of the main factors influencing the base shear is the building's mass, which takes into account the weight of all the structural elements, furnishings, and people. Higher base shear forces are often experienced by heavier constructions.

Building codes and standards, for example, give guidance for seismic design parameters that specify the seismic pressures that structures must be able to endure. These standards include several elements, including the amount of seismic danger, ground motion characteristics particular to the location, and structural system qualities. Base shear is calculated, and structures are constructed to resist the expected seismic forces using the seismic design criteria outlined in building regulations.

To correctly determine the building's dynamic reaction to seismic motion, dynamic analysis techniques like modal analysis, response spectrum analysis, or time history analysis are used. Calculating the base shear requires an understanding of the building's inherent frequencies, mode shapes, and dynamic properties, all of which are much enhanced by these analyses. Engineers are able to precisely predict the lateral forces operating on the building and account for the dynamic behavior of the structure by adding the findings of dynamic analysis into the base shear calculation.

In general, base shear calculation is an important part of the seismic design process because it gives engineers information, they need to build buildings that can survive the lateral pressures caused by earthquakes. Through the use of dynamic analysis findings, building mass, and seismic design standards, engineers can precisely calculate base shear and create earthquake-resistant designs that put occupant safety and stability first in seismically active areas.

Story Shear Distribution

In structural engineering, evaluating the structural integrity and performance of the overall structure requires an understanding of the story shear distribution—the distribution of shear forces throughout a building's height. Particularly during seismic events or severe winds, shear pressures—lateral forces operating parallel to the plane of the structure—can significantly stress different structural components and connections.

Analyzing the vertical distribution of shear forces throughout the building is necessary to evaluate the story shear distribution. This entails looking at how shear pressures differ in strength between stories and locating possible hotspots for concentrated high shear stress. Engineers can determine crucial spots where shear forces are most noticeable and develop suitable structural parts to efficiently withstand these stresses by analyzing the tale shear distribution.

Numerous factors, such as the building's geometry, structural system, and lateral load-resisting parts, affect the distribution of shear forces. Non-uniform shear distributions can arise in tall structures with asymmetrical layouts or irregular geometries; greater shear forces might occur at specific spots because of the geometry of the building. Shear forces can also be transferred and distributed differently within a structure depending on the kind of structural system used, such as moment frames, shear walls, or braced frames.

It is essential to comprehend the story shear distribution in order to guarantee the building's structural integrity and stability throughout a range of loading scenarios. Engineers may design structural components and connections to withstand shear pressures and minimize probable failure modes, such as shear buckling or overstressing of structural parts, by studying how shear forces are distributed over the height of the structure.

In addition, engineers may improve the design of lateral load-resisting systems and make sure that shear forces are efficiently transported and dispersed throughout the structure by analyzing the tale shear distribution. To improve overall structural performance and resilience, this may entail spreading shear stresses through the use of moment frames, braces, or shear walls positioned strategically throughout the structure.

In conclusion, examining the story shear distribution is an essential component of structural design, especially in areas that are vulnerable to earthquakes or strong winds. The distribution of shear forces vertically inside a structure may help engineers create strong and resilient designs that put occupant safety and structural integrity first under a range of loading scenarios.

Drift Calculation

Drift calculation is an essential phase in structural engineering that determines how structures respond to seismic loads and guarantees that building codes and standards are followed. The word "drift" describes the lateral displacement or deformation that a structure experiences during seismic events, and it is a significant factor in determining the building's overall performance and stability.

Evaluating the relative displacements between building floors under seismic loading circumstances is the main goal of the drift calculation. Engineers may determine how the structure will flex or deform during an earthquake and make sure that the resulting displacements do not exceed the limitations specified in building codes or standards by measuring the magnitude of drifts.

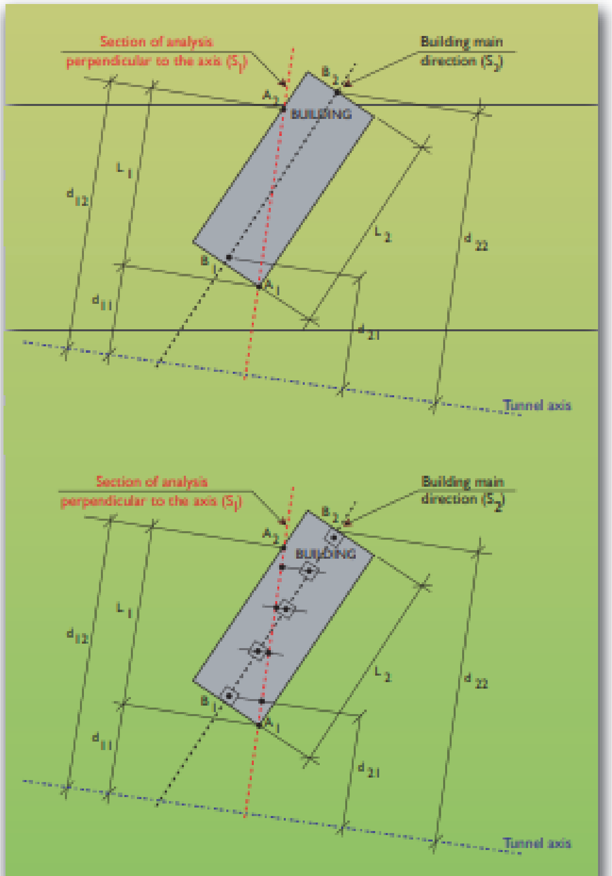
Maximum permitted drift limits are usually specified by building standards and depend on many criteria, including building height, occupant type, and seismic danger level. By prohibiting severe deformations that might jeopardize structural stability or result in structural failure, these limitations are designed to preserve the structural integrity of buildings and ensure the safety of its inhabitants.

Engineers use advanced structural analysis techniques, such as modal analysis, response spectrum analysis, or time history analysis, to examine the dynamic response of the structure in order to determine drift. Engineers can forecast how the building will respond to seismic loads thanks to these studies, which provide light on the building's inherent frequencies, mode shapes, and dynamic features.

Engineers take into account a number of variables during the drift calculation process, such as the building's geometry, structural design, lateral load-resisting systems, and soil-structure interaction effects. Engineers are able to evaluate regulatory compliance and make precise predictions about potential drifts across tales by integrating these aspects into their research.

Engineers compute the drifts and compare the findings to permitted limitations found in building regulations or standards. To reduce excessive deformation and guarantee regulatory compliance, relevant design adjustments or reinforcing measures can be required if the predicted drifts exceed allowable limits.

To sum up, drift computation is an essential component of seismic design and analysis that enables engineers to assess how structures react to seismic loads and guarantee adherence to building codes and standards. Engineers are able to design resilient buildings that prioritize structural integrity and occupant safety while withstanding seismic shocks by properly forecasting drifts between stories.



❑ SHALLOW SPREAD FOUNDATIONS

The control parameters are calculated at least along two directions:

– direction S_1, perpendicular to the tunnel centreline, intercepting the longest segment (L1) on the planimetry of the building or passing through the corner of the building perimeter that is closest to the tunnel axis;
– the direction S_2 that coincides with the main axis of the building, being the analysis done along the L_2 segment.

Hence, calculations are performed along segments A_1–A_2 and B_1–B_2, respectively.

❑ ISOLATED FOUNDATIONS

The control parameters are calculated along the same directions S_1 and S_2, but at the location of the isolated foundations (S_1) or at the location of their projection on the segment along which the calculation is performed (S_2).

Figure 8. Example of calculation sections for buildings within the control zone (Vittorio Guglielmetti P. G., 2008)

Design of Members and Connections

Strength of Member

For a structure to remain stable and intact throughout an earthquake, structural engineers must design components and connections to withstand seismic stresses. In order for walls, columns, and beams, among other structural elements, to sustain the expected moments and forces brought on by seismic loading, their strength needs to be properly evaluated.

Finding the anticipated seismic moments and forces that would affect the structure during an earthquake is the first step in the design process. These forces are computed according to the location of the structure, the degree of seismic danger, the kind of occupancy, and the structural layout. Structural components are scaled and specified to efficiently resist seismic forces after they have been calculated.

Walls, columns, and beams are examples of structural elements that are made to be strong and ductile enough to endure expected seismic stresses. A material or structure is said to be ductile if it can undergo plastic deformation without breaking suddenly, which enables it to efficiently absorb energy and disperse seismic forces. To improve the strength and ductility of structural components, strengthening techniques including enlarging the cross-sectional area, utilizing high-strength materials, or adding more reinforcement may be used.

Shear walls in particular are crucial elements of seismic-resistant constructions since they are made to withstand the lateral strains brought on by seismic activity. In order to increase the walls' strength and ductility, reinforcement—both vertical and horizontal—is usually added. To enhance the walls' performance under seismic loads, additional details such confinement reinforcement and boundary components may be included.

Ample ductility and strength are guaranteed when designing columns and beams to withstand lateral stresses as well as gravity. In order for columns to endure the axial and flexural forces caused by seismic loading, longitudinal and transverse reinforcement is used. Similar reinforcement is used in beams to withstand shear stresses and bending moments, and its detailing is designed to promote ductility and ward off brittle failure modes.

Under seismic pressure, connections between structural parts are essential to guaranteeing the building's overall stability and integrity. Connections are made to transfer forces effectively while allowing for the displacements and deformations that are expected during an earthquake. To guarantee the strength and resilience of connections under seismic loading circumstances, special detailing is used, such as moment-resisting connections and ductile detailing.

To put it succinctly, designing members and connections with seismic resistance in mind entails making sure that structural components are sufficiently specified, scaled, and strengthened to survive the anticipated seismic moments and stresses. Engineers may design resilient buildings that can safely resist seismic occurrences, safeguarding building occupants and limiting damage by giving ductility and strength top priority during the design phase.

Connection Design

In structural engineering, a building's overall performance and durability under seismic loading circumstances depend heavily on the design of the connections between structural components. In order to be ductile under cyclic stresses and strong enough to survive the expected demands placed on them by earthquakes, connections need to be properly engineered.

In particular, beam-column connections are essential for conveying forces between beams and columns and for allowing for the displacements and deformations that are predicted during seismic activity. These connections are susceptible to failure if not correctly engineered since they are subjected to large shear stresses and bending moments. The ductility and strength of beam-column connections are specifically checked for in order to guard against brittle failure modes and guarantee structural stability as a whole.

Another crucial component of connection design in earthquake-resistant buildings is wall-to-wall connections, particularly in those with masonry or shear walls. In the case of a seismic event, these connections must be able to transfer lateral loads across neighboring walls while permitting differential movements and deformations. The ductility and robustness of wall-to-wall connections can be improved by using special details, such as anchor bolts, shear connectors, and reinforcing ties.

The transmission of lateral loads from the building's diaphragms, such floors or roofs, to the lateral load-resisting system, like shear walls or moment frames, depends on the diaphragm-to-collector connections. These connections need to be built to effectively distribute seismic stresses and allow for the diaphragms' anticipated displacements and deformations. Under seismic stress conditions, the entire stability and integrity of the structure depend on the proper detailing and strengthening of the diaphragm-to-collector connections.

Engineers take into account several elements, including material qualities, loading circumstances, displacement capabilities, and detailed needs, when designing connections to withstand seismic activity. In order for the structure to disperse seismic energy and survive the stresses exerted by earthquakes, ductility is prioritized in order to guarantee that connections may experience considerable deformations without experiencing unexpected collapse.

For the purpose of maximizing ductility and resilience in connection design and evaluating the performance of connections under seismic stress, sophisticated analytical methods like finite element analysis and nonlinear modeling may be utilized. Furthermore, experimental research and physical testing may verify design ideas and offer important insights into how connections behave in real-world earthquake scenarios.

In seismic-resistant structural engineering, connection design is a crucial component that necessitates careful consideration of ductility, strength, and performance under cyclic loading situations. Through the prioritization of resilient connection design, engineers may build structures that can endure seismic disasters safely while safeguarding the people and property inside.

Evaluation of Performance

To make sure a building can sustain the expected stresses and deformations during a seismic event, a number of factors need to be carefully considered. Assessing the building's energy dissipation during seismic occurrences is a critical component in limiting damage and guaranteeing occupant safety. In order to absorb and disperse seismic energy and lessen the stresses communicated to the building's components, energy dissipation mechanisms—such as yielding elements or damping devices—are introduced into the structural design.

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Another important consideration when evaluating a building's performance under seismic loads is its deformation capability. The structure needs to be able to flex and experience significant displacements without losing its overall stability and integrity. The ductility of structural components and connections, as well as their potential to withstand large deformations without developing brittle failure modes, are taken into account when evaluating the deformation capacity. This guarantees that the structure will be able to bear the seismic pressures without collapsing or suffering permanent damage.

A key component of performance evaluation is overall structural integrity, which includes the building's capacity to continue to be stable and operational both during and after a seismic event. This involves making the structure satisfies all relevant limit states, including the specifications for strength, stability, and serviceability outlined in building regulations or standards. While stability limit states deal with concerns linked to general stability and resistance to overturning or collapsing, strength limit states guarantee that the structure can bear the expected loads without going over its capacity. Serviceability limit states take occupant comfort and structural durability into consideration while focusing on preserving the structure's usability and performance under typical operating circumstances.

A building's response to several seismic situations, such as the design-level seismic event mentioned in building codes or standards, is also evaluated as part of the performance evaluation process. In order to evaluate the structure's behavior and reaction, this entails simulating seismic loads on the structure using analytical models or physical testing methods. It is possible for engineers to make sure that a building satisfies the safety and performance standards for seismic occurrences by comparing its performance to predetermined criteria and limiting states.

To summarize, the assessment of a building's seismic performance include determining its overall structural integrity, deformation capacity, and energy dissipation capabilities. Engineers can guarantee a structure's safety and resilience in the case of an earthquake by confirming that it satisfies all applicable limit states and is capable of withstanding the expected stresses and deformations.

Reporting and Documentation

Comprehensive reports that describe the computational procedure, analytical conclusions, and design considerations must be provided throughout the reporting and documentation phase of the seismic performance evaluation. These papers are important documentation of the evaluation procedure and a foundation for comprehending the behavior of the structure under seismic stresses. The procedures used in the study, such as the choice of analytical techniques, input parameters, and evaluation-related assumptions, should be described by engineers.

Key observations and conclusions from the research should be highlighted in a clear and succinct presentation of the analytical findings. This may include any possible weaknesses or vulnerabilities found in the structural system, as well as the building's reaction to seismic loads, including deformations, stresses, and displacement patterns. When presenting the results, engineers should make efficient use of tables, graphs, and drawings. These visual aids help to clarify the structural reaction.

Furthermore, the report should specify any structural reinforcing or retrofitting procedures that are considered required to enhance the building's seismic performance. This might entail suggestions for improving the building's resistance to seismic hazards by adding dampening devices, changing connections, or reinforcing the building's current structural components. For any planned interventions, engineers should submit comprehensive design concepts and specifications, as well as an estimate of the anticipated improvements in structural performance.

Through compliance with these computation sections and comprehensive reporting and documentation, engineers are capable of assessing the seismic performance of structures located in the control zone with proficiency. By doing this, it is made sure that those involved in the building's safety and robustness may make well-informed judgments about its behavior under seismic stresses. The ultimate objective is to put into practice appropriate design techniques that improve structural resilience and lessen the dangers related to seismic occurrences.

3.5.2 Face stability

An essential component of making sure tunnel excavation activities are both safe and effective in mechanized tunneling is face stability risk assessments. The area of the tunnel excavation that is visible and where the Tunnel Boring Machine (TBM) or other excavation machinery comes into contact with the surrounding earth is referred to as the "face". Face stability is crucial for averting cave-ins, collapses, and other dangerous situations that might put workers in peril and jeopardize the tunnel's structural integrity.

Mechanized tunneling projects frequently use numerical techniques, such finite element analysis (FEA) and finite difference method (FDM), to evaluate face stability. With these techniques, the behavior of the earth and the excavation machinery is modeled under a range of loading scenarios, including cutterhead torque, TBM thrust, and ground stresses. Engineers can assess variables including ground strength, geological conditions, and the efficiency of ground support systems in preserving face stability by modeling these relationships.

Furthermore, during excavation, observational approaches including monitoring protocols and empirical correlations are frequently employed to evaluate face stability in real-time. These techniques entail keeping an eye on variables including ground motions, convergence rates, other TBM performance indicators in order to spot unstable patterns early and take appropriate action.

Face stability risk analysis includes determining plausible failure mechanisms, evaluating the possibility and impact of these failures, and putting risk-reduction strategies into action to reduce the possibility of unfavorable outcomes. To strengthen the stability of the face, common mitigation strategies include modifying the parameters of the excavation, adding more ground support, and putting ground improvement procedures into practice.

To ensure the safety and success of tunnel excavation operations, face stability risk analysis in mechanized tunneling, as a whole, comprises a multidisciplinary approach that blends observational methods, numerical modeling, and risk management concepts. Through a methodical assessment and mitigation of face stability problems, engineers may reduce risks, enhance excavation procedures, and produce tunneling projects of superior quality.

To keep the working face stable when excavating a tunnel, temporary active support is frequently needed. Applying a Slurry Shield (SS) or an Earth Pressure Balance Shield (EPBS) uses slurry that completely fills the work chamber under pressure, or freshly dug earth to give continuous active support to the tunnel face. For EPBS, the supporting pressure is obtained by managing the materials entering and leaving the chamber, that is, by controlling the speed at which the excavation advances and the rotation of the screw-conveyor.

More and more tunnels in saturated soils are being built using closed shields, which eliminates the need for needless interventions like ground freezing, injections, and ground lowering. By continuously supporting the tunnel face during excavation, this contemporary tunneling technique reduces the danger of face failure and allows for the management of surface settlement. Inadequate face support can result in global collapse in the extreme when slide lines reach the surface, as well as tunnel-face instability. When this occurs, the machine excavates a larger area than the theoretical excavation volume would indicate.

Analytical Method

A chimney and occasionally a crater are created on the ground surface as the collapse advances toward the surface. Excessive subsidence and damage to structures above are the subsequent outcomes of the heading failure. A direct passage between the machine chamber and the water will open while tunneling beneath a lake, river, or seabed. In addition to creating tunnel face instability, seepage flow toward the face can also result in an increase in effective stresses and a drop in the piezometric head in the surrounding ground. Following that, the earth consolidates, causing surface settlement. (Anagnostou & Kovári, 1994)

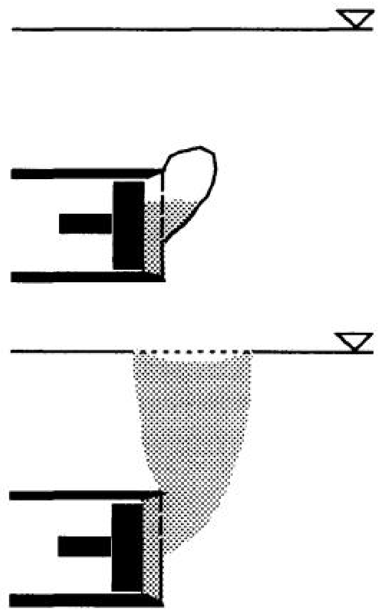


Figure 9. Typical patterns of failure (Anagnostou & Kovári, 1994)

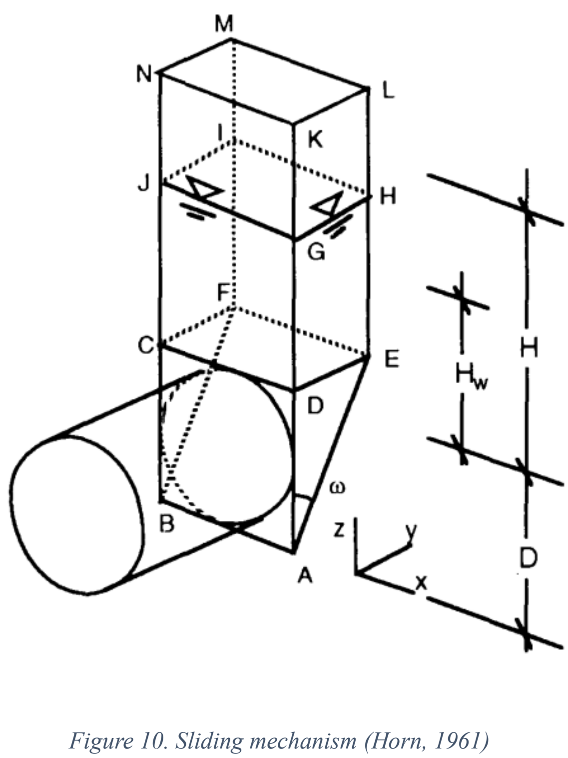


Figure 10. Sliding mechanism (Horn, 1961)

The following is a summary of several pertinent examples where analytical methods were used to calculate face pressure. TBM-EPB was used to dig tunnels.

The Porto Metro (a 70-kilometer light rail system centered on Porto, Portugal) has two tunnels (Line C, 2.5 km, and Line S, 4 km) that are propelled by two EPBs with diameters of 8.7 m and 8.9 m, respectively, and cover an area of 3÷30 m. The ground is made of coarse granite, and because there are numerous river systems, alluvial material is frequently found above the worn granite.

The surface topography's form is approximately followed by the groundwater table. The fundamental pressure reference in this instance was determined to be $\sigma_T = \sigma_W + 0.6$ bar. The effective ground thrust, which is determined using the Anagnostou-Kovari technique and accounts for the worst geotechnical circumstances ($\sigma'_T = 0.2$ bar plus an extra safety buffer), is the second element in the equation. In practice, the effective pressure that results in the same as if the Anagnostou-Kovari calculations had assumed an FS of 2.

The metro system in Turin, Italy is made up of a single, 6.8-meter-diameter circular tube that houses a double-track line with an average platform depth of around 17 meters. The geological environment is made up of fluvial-glacial and fluvial deposits, as well as vertical discontinuous layers (lens) with varied cementation levels, degrees of grain size dispersion, and potential shallow water table presence. The planned pressure for the excavation was $\sigma T = \sigma + 0.3$ bar, where σ represents the pressure computed using Anagnostou-Kovari with Fs = 2. This was done to account for any plenum variations.

Bologna, Italy has a new subterranean train connection: Most of the future High Speed Rail Line Milan-Naples' portion that passes through the densely populated city of Bologna is expected to be subterranean. There were two 9.4-meter-diameter EPB single-track tunnels employed (tunnel axis distance: 15 meters, overburden: 15·21 meters). Nine "homogeneous" zones were identified in the alignment according to the predominate ground conditions, which included soft coastal clays, sands, and alluvial deposits. Applying face pressure with a value that matched the value found using the Caquot-Kerisel/Carranza technique with an FS = 2 allowed for an acceptable management of the settlements.

Spasskaya Metro (Saint Petersburg, Russia): 10.7-meter-diameter escalator tube with a 100-meter length and a 30-degree slope that connects to the current subterranean Spasskaya Metro Station. The excavation was done in challenging soil conditions with water pressure (soft clay and sand). The face-support pressure profiles were developed throughout the design phase using analytical techniques (Hydro-geologic equilibrium condition, Caquot method, Dutch Onderground Bowen Center method). After choosing various scenarios and pressure profiles, a number of three-dimensional numerical studies (FLAC 3D) were carried out to replicate the chosen situations. Ultimately, a successful excavation was achieved by using the pressure profile according to the Caquot technique with $F_s = 2$.

Maldonado Project (Buenos Aires, Argentina): the project transfers surplus water to the Rio de la Plata by diverting flood flow in Buenos Aires from three locations along the Maldonado River culvert into two flood control tunnels (10 km and 5 km long, 6.90 m diameter). The planned pressure for the two tunnels that were excavated above the water table was based on the Fs = 2 Caquot technique.

Caquot-Kerisel Method (1994 & 1996) - Carranza-Torres' Integrated EPB Shield Solution

Theorems of plasticity's lower and upper bounds provide statistically admissible solutions, which are typically seen to be more rigorous than limit equilibrium solutions. The solutions of Caquot are among the statically permissible ones; they are obtained for 2D circular tunnel sections, but they are readily expanded to take into account a 3D spherical geometry.

The equilibrium requirement for material failing above the crown of a shallow circular (cylindrical or spherical) hollow is taken into account by Caquot's model.

The material has a unit weight □ and a shear strength defined by Mohr-Coulomb parameters c (cohesion) and φ (friction angle), while the distribution of vertical stresses before excavation is lithostatic and the ratio of horizontal to vertical stress is 1. A support pressure ps can be applied inside the tunnel, while a surcharge qs (from infrastructures or embankments) acts on the ground surface.

For the situation presented below Caquot’s solution defines the value of internal pressure (ps) as the minimum or critical pressure below that the tunnel will collapse. The Caquot generalized solution can be represented by the following equation developed by Carranza-Torres (2004):

$$\frac{p_s}{\gamma a} = \left(\frac{q_s}{\gamma a} + \frac{c}{\gamma a} \times \frac{1}{\tan\phi}\right)\left(\frac{h}{a}\right)^{-k(N_\phi - 1)} - \frac{1}{k(N_\phi - 1) - 1}\left[\left(\frac{h}{a}\right)^{1-k(N_\phi - 1)} - 1\right] - \frac{c}{\gamma a} \times \frac{1}{\tan\phi}$$

where:

p_s = support pressure;

q_s = surcharge load;

a = tunnel radius;

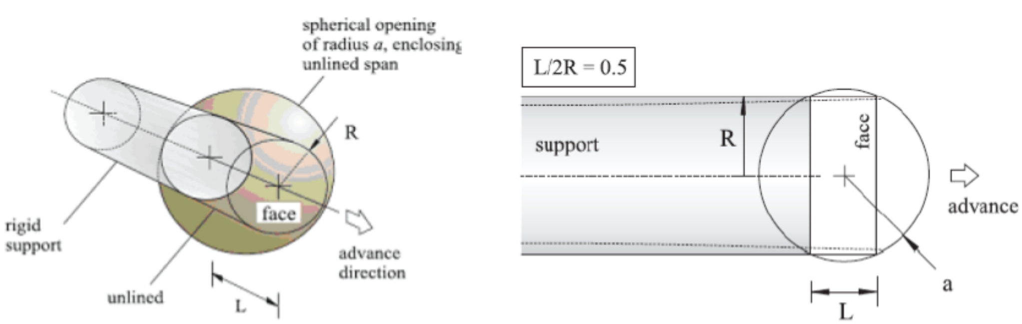
c, ϕ = Mohr-Coulomb parameters;

h = depth of tunnel from axis;

k = parameter that dictates the type of excavation [1 = cylindrical tunnel; 2 = spherical cavity];

γ = unit weight;

N_ϕ^{FS} = function of FS factor of safety



$$a = \sqrt{\frac{L^2}{4} + R^2}$$

Figure 11. Calculation of the modified tunnel radius for face stability analysis

It should be noted that previous equation is valid only when the given Mohr-Coulomb parameters lead to a state of limiting equilibrium – the situation in which the excavation is about to collapse. In general, the strength of the material will be larger than the strength associated with the critical equilibrium state of the cavity.

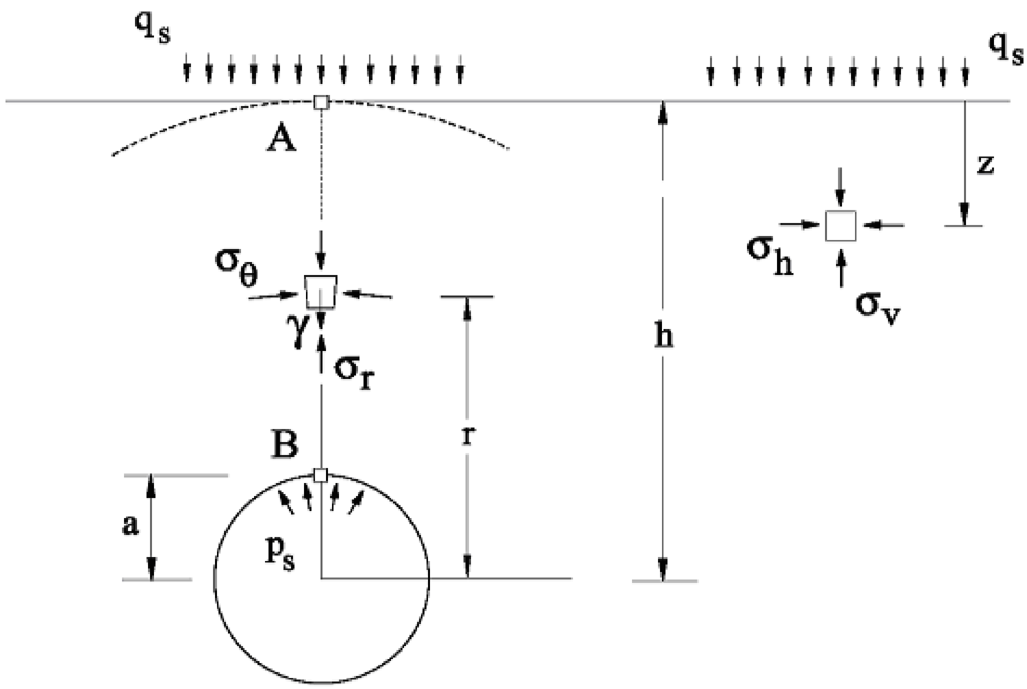


Figure 12. Basic scheme for the Caquot-Kerisel solution

The factor of safety FS is defined as "the ratio of actual Mohr-Coulomb parameters to the critical Mohr-Coulomb parameters", as expressed in the following equations (Strength Reduction Method, Dawson et al. 1999), this approach assumes a proportional reduction of the Mohr-Coulomb parameters.

$$N_{\phi}^{FS} = \frac{1+\sin\left(\tan^{-1}\dfrac{\tan\phi}{FS}\right)}{1-\sin\left(\tan^{-1}\dfrac{\tan\phi}{FS}\right)}, \quad FS = \frac{c}{c^{cr}} = \frac{\tan\phi}{\tan\phi^{cr}}$$

Method of Anagnostu & Kovari (1994 & 1996) Solution for EPB Shield

Face stability in homogeneous ground is assessed considering the limit equilibrium of a wedge loaded by a prismatic body. This sliding mechanism was proposed by Horn (1961), and it takes into account the formation of slip surfaces which are frequently observed in failures of tunnel faces in shallow tunnels. Mohr-Coulomb failure criterion and drained conditions are assumed in this case. The load of the prism is computed based upon the silo-theory (Janssen 1895) allowing for the reduction in vertical effective stress on the active wedge due to arching. (Lenczner, 1963)

Since the work chamber of an EPB is filled with excavated soil under pressure, a distinction must be drawn between the total and effective stress acting upon the face. Only the effective normal stress can be denoted as actual support pressure on the excavation face. This will be termed "effective support pressure" and denoted s' as shown in figure below. If the pore water pressure, the piezometric head h_F in the work chamber is lower than the piezometric head h_0 in the undisturbed state, then the ground water will seepage through the tunnel face. If not controlled, it can be cause of face failure.

At limit equilibrium the effective support pressure s' depends on the tunnel diameter D, on the overburden H, on the piezometric head on the chamber h_F, on the elevation of the water table h_0, on the shear strength parameters c and ϕ and on the submerged weight γ'.

Using dimensional analysis and by taking into account the linearity of equilibrium and failure equations, the following general form of the limit equilibrium condition has been proposed (Anagnostou & Kovari 1996):

$$s' = F_0 \gamma' D - F_1 c + F_2 \gamma' \Delta h - F_3 c \Delta h / D$$

where $F_{0\text{-}3}$ are dimensionless coefficients that depend on the friction angle ϕ, on the geometric parameters H/D and $(h_0\text{-}D)/D$, and on the ratio of the dry to submerged unit weight γ_d/γ', for a γ_d/γ' ratio of 1.6, which has a good enough approximation for practical purposes.

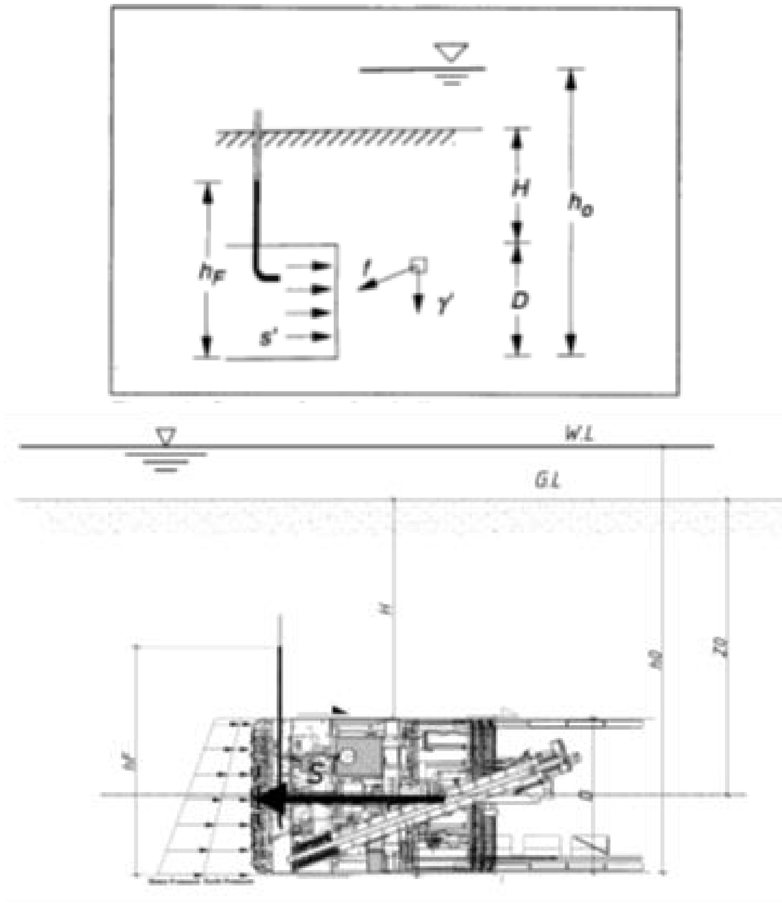


Figure 13. Seepage force f and effective support pressure s' in a EPB operation

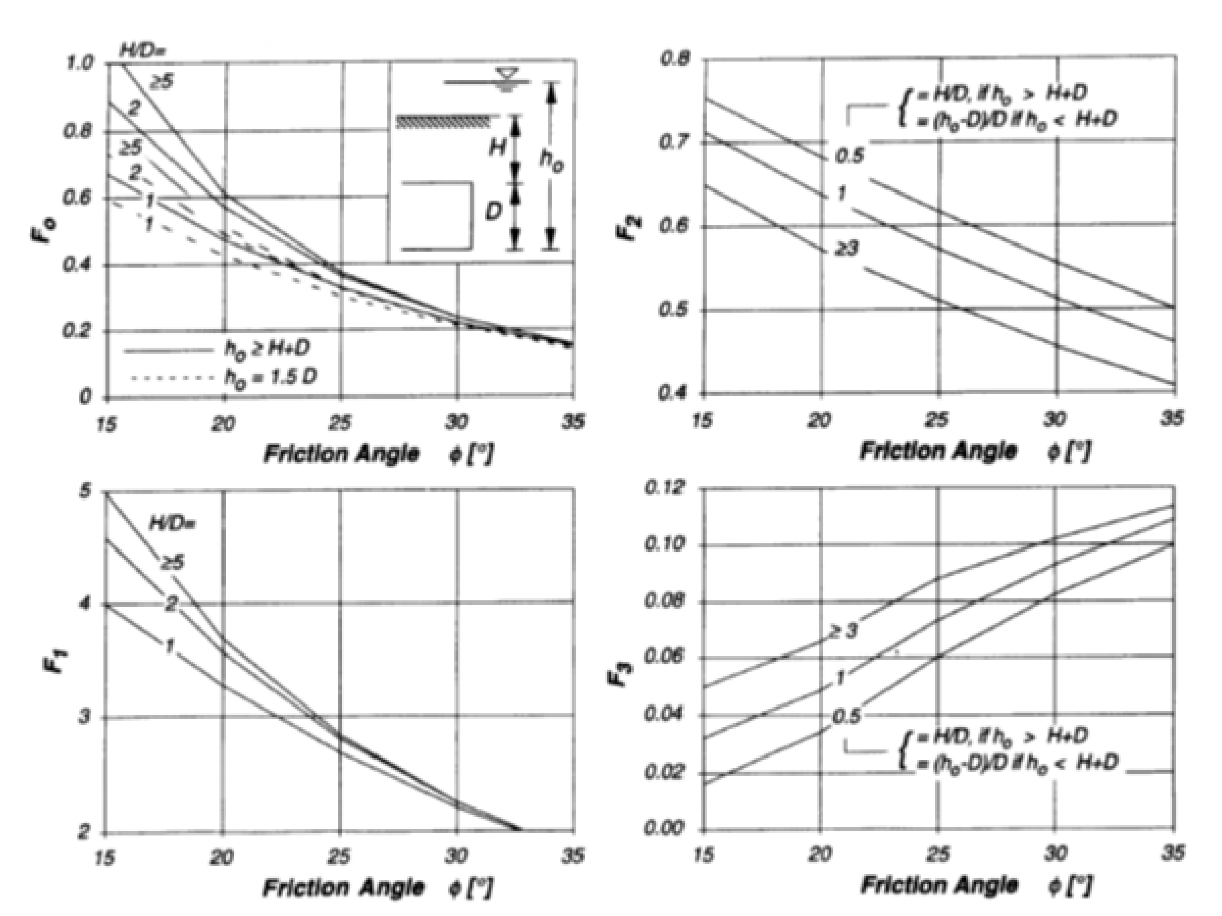


Figure 14. Normograms for the dimensionless coefficients F0-3

Numerical Method

Ensuring the safety and success of excavation operations requires evaluating the Advance Face (ACE) stability in mechanized tunneling using numerical analysis. The intricate interactions between the Tunnel Boring Machine (TBM), ground conditions, and operating factors affect the ACE, which is the active working region of the tunnel face where excavation is taking place. Finite element analysis (FEA) and finite difference method (FDM) are two numerical techniques that are widely used to simulate and assess ACE stability.

Engineers may create extensive models of the behavior of the ACE under different loading circumstances by discretizing the ground and surrounding structures into finite elements or grid points, respectively, using

FEA and FDM. These models anticipate ground deformations, stresses, and displacements by taking into account variables including ground characteristics, TBM thrust, cutterhead torque, and support system efficacy. Engineers are able to evaluate the ACE's stability and pinpoint possible causes of failure, such as excessive convergence, face collapse, or ground heave, by precisely simulating these interactions.

Sensitivity studies and parametric analyses to assess the impact of various factors on ACE stability are also made easier by numerical analysis. Engineers can look at how different support system designs, TBM operation settings, and ground conditions affect the possibility of stability problems. The improvement of excavation techniques and support measures to improve ACE stability and reduce hazards is made possible by this iterative approach.

Moreover, numerical models can incorporate real-time monitoring and feedback systems to offer continuous evaluation of ACE stability throughout excavation. Convergence measurements, ground settlements, and TBM performance parameters are examples of instrumentation data that may be included in the analysis to support field decision-making and validate model predictions.

In conclusion, engineers can assess and control the hazards related to excavation activities in a thorough manner thanks to the numerical study of ACE stability in mechanized tunneling. Engineers may improve safety procedures, optimize excavation designs, and guarantee the timely completion of tunneling projects by utilizing cutting-edge computational approaches.

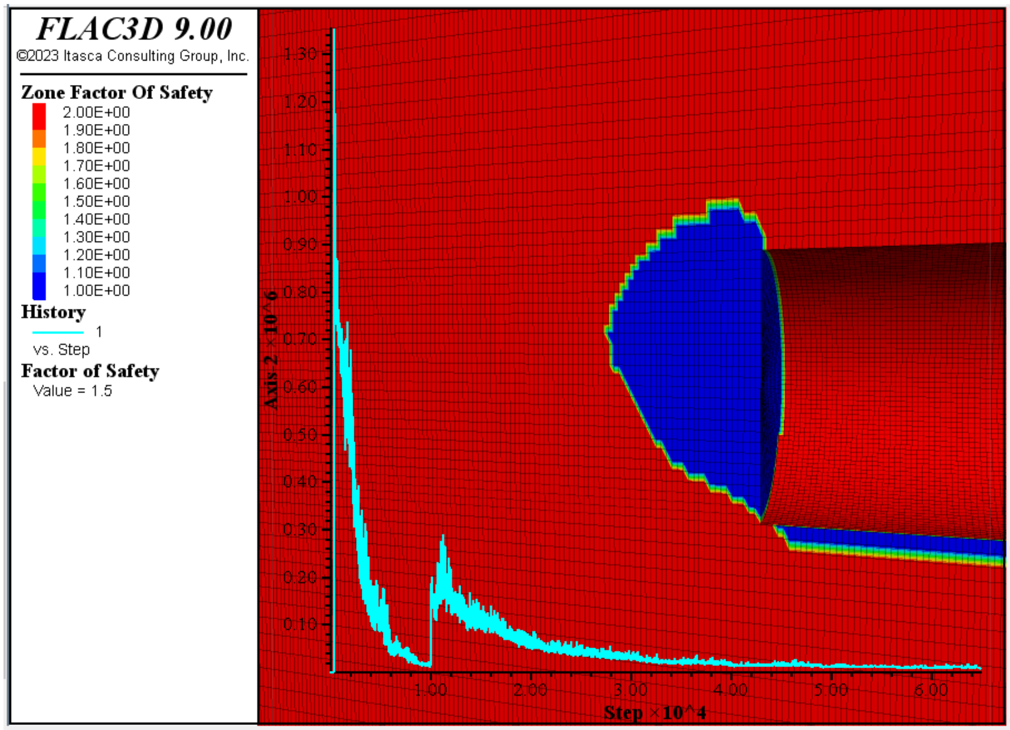


Figure 15. Numerical Analysis Model of Face Stability Assessment

3.5.3 Settlements

Ground movement predictions have been assessed for the TBM excavation. The following variables are associated with the extent and profile of ground surface impacts:

- geological characteristics unique to the site.
- Cover-depth to the excavation below ground.
- techniques of excavation (TBM).

"Short-term" settlement is the phrase used to describe the settlement caused by excavation; after the tunnel face has progressed past a certain point, the tunneling construction activities have no further effect on settlement. Settlement has leveled off at a rather steady amount. Long-term creep or consolidation effects might cause this short-term value to fluctuate.

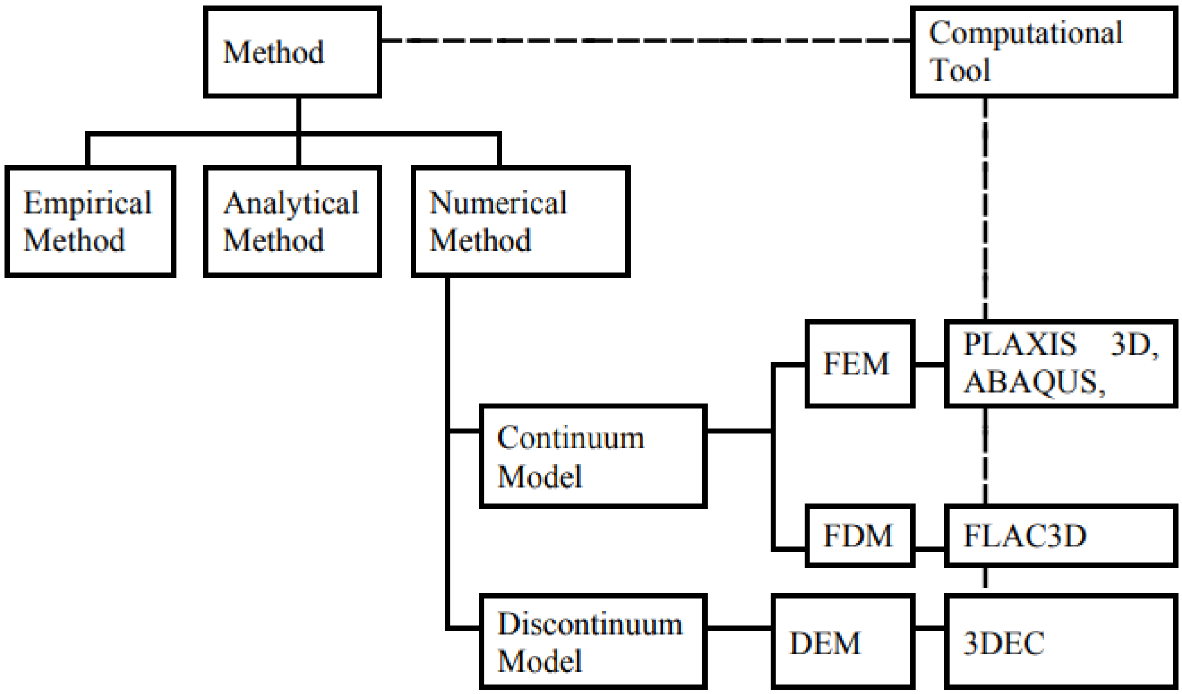


Figure 16. Different methods for prediction of settlements & computational tools (S. M. Yahya, 2014)

3.5.3.1 General Approach

Estimating settlements at the ground surface is necessary for the building of urban tunnels. These communities might have detrimental effects on nearby tunnel alignments as well as on ground-level constructions now in place.

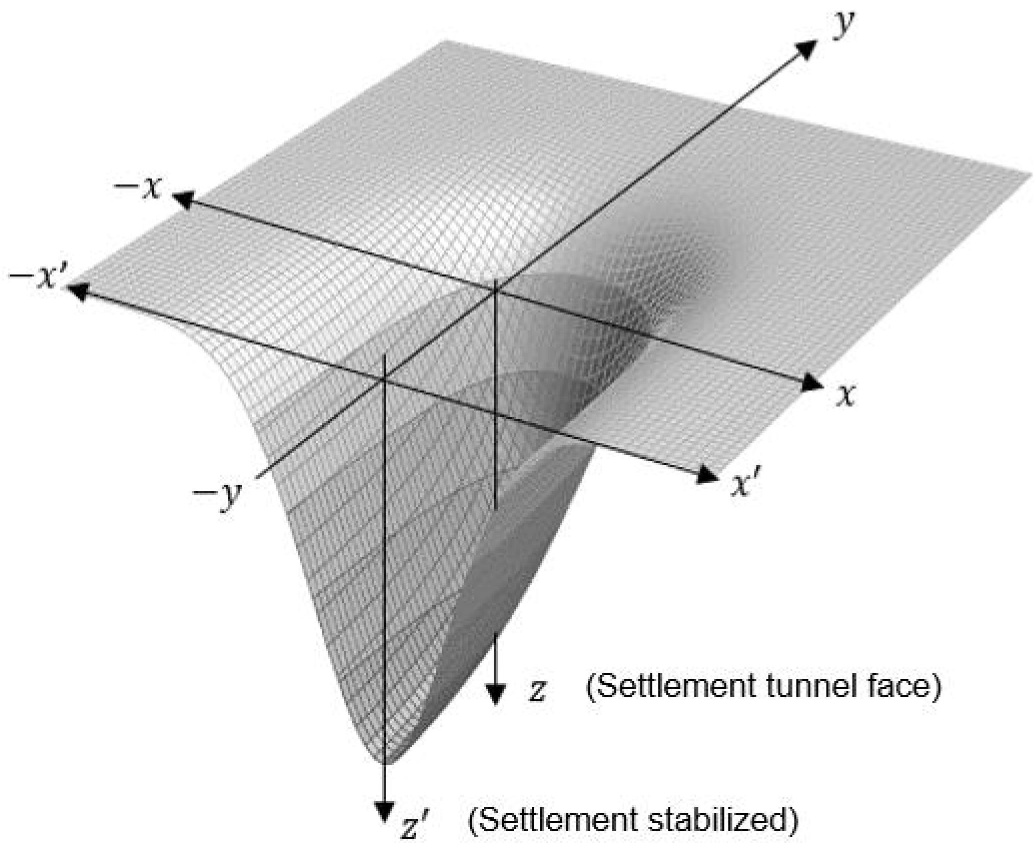


Figure 17. Settlements trough above an advancing tunnel

Both analytical and numerical techniques can be used to estimate ground settlement. Settlements, slopes, and horizontal deformation are included into a GIS tool based on analytical parameters and methodologies, enabling their mapping, and indicating the greatest deformations structures inside the tunnel's zone of effect (so-called ZOI). The area where settlements bigger than 1 mm occur is known as this zone. The GIS tool made it possible to choose the maximum displacement values beneath the footprint of any building inside the ZOI automatically. Following the completion of the study of settling, slope, and horizontal deformation (tensile strain), structures along the tunnel alignments must be inspected for potential damage from tunneling displacements.

By comparing the derived maximum absolute settlement, slope, and horizontal deformation values with the threshold values, the damage category of the structures is assessed. The most important alignment parts that call for specific numerical computations will be identified by this preliminary investigation.

3.5.3.2 Analytical Method

When tunneling through soft ground, there are a number of possible causes for ground displacements. As the tension relaxes during tunnel excavation, the supported earth surrounding the tunnel flows within. This is because of things like:

Face loss as a result of decompression at the tunnel face: as a confinement pressure is applied, material is removed from the tunnel face by the shield's revolving cutters. The earth surrounding the tunnel face and in a zone of effect ahead tends to protrude out of the face despite the applied pressure. The volume loss at the excavation face, often known as "face loss," results from this.

Shield loss as a result of the cutterhead's slightly bigger diameter than the shield and the conicity between the front and tail shields. These elements facilitate the shield's advancement by lessening the possibility that it will become trapped and by enabling steering around bends. The hollowed-out hole can therefore converge radially. Furthermore, shield loss may eventually rise due to overcutting. The pace at which the soil deforms in relation to the tunnel progress rate determines the extent of this convergence. As a result, the shield may be entirely or partially enclosed by the excavated perimeter.

tail void loss, which depends on the backfill injection's volume, pressure, and accuracy at the tail void around the tunnel lining that has been placed. There appears to be an additional radial convergence increase.

Ground loss during backfill grouting as a result of liner deformations. By moving the overburden pressure to the new boundary, radial losses persist.

Resolution for the long-term pertaining to consolidation. Tunnels will settle over time as a result of secondary and time-dependent consolidation of the surrounding soil. The amount of post-construction settlement brought on by tunneling disturbance is influenced by two factors: (i) the characteristics of the soil and (ii) the methods used during construction, such as face pressure, driving speed, and grout injection pressure and volume. Whereas higher settlement and perhaps longer stabilization times occur in compressible clayey soil, sand and silts often experience less settlement and swiftly reach the ultimate stable state (thus, unless time-dependent soil behavior is observed, this component is rather unimportant).

The total "volume loss," or V_L, resulting from the tunnel's excavation, is equal to the sum of the radial and face losses. Thus, the amount of soil that has been dug over the theoretical design volume is known as volume loss (or ground loss). It is stated in terms of m³ per meter of tunnel advance, or as a percentage of the ultimate tunnel volume. As the tunneling process continues, a settling trough develops at the surface as a result of the volume loss. The kind of soil and the tunneling technique determine the settling trough's form. A closed-face automated tunneling system like EPB-TBM can reduce the amount of volume loss.

Following common practice and the contractual value for max. allowable volume loss (V_L=1.0%), two volume loss scenarios are considered to address uncertainties:

- V_L=0.5%, expected scenario.
- V_L=1.0%, conservative scenario.

Predicting "greenfield" ground settlement is crucial, presuming there are no buildings above the tunnel, even if the presence of existing structures at the ground surface might alter the evolution of ground movements. The longitudinal displacement trough and transversal displacement at the surface closely resemble the curves of a normal Gaussian distribution and the cumulative Gaussian distribution, respectively.

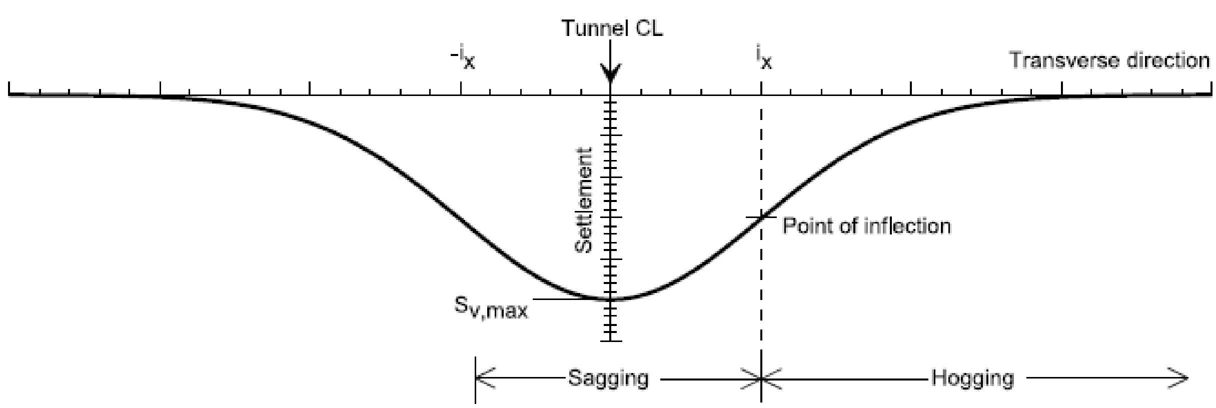


Figure 18. Transversal settlement trough

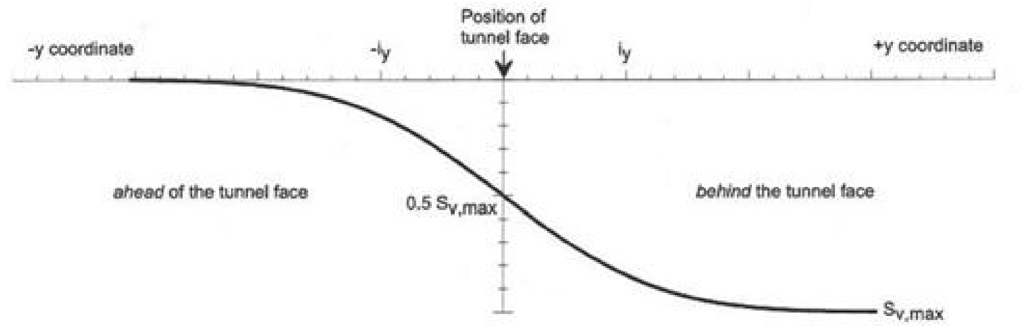


Figure 19. Longitudinal settlement trough

The larger of the two extents of the contours representing ground surface settlement caused by 1 mm excavation is the Zone of Influence for ground movement. The prospective ZOI is thought to include structures and subterranean utilities that are situated inside the lines drawn by the aforementioned zones. They are now listed among the buildings and properties that might be impacted by ground displacement in the register. The kind of structure, its state at the time, and the uneven settling across the structure all affect the possibility of damage to the structure.

A key consideration in tunnel design is the estimation and mitigation of damage from ground movements brought on by construction. This is a particularly significant issue for shallow tunnels dug on soft soils, where it could be necessary to take costly corrective action before building, such compensating grouting or structural underpinning. (Federico Pinto, 2013)

The Gaussian distribution function, represented by the letter F, is commonly used to characterize the surface settlement of a circular tube with radius R. The probability density of settlement at various separations from the tunnel axis is represented by this function. The bell-shaped curve of the Gaussian distribution, also referred to as the normal distribution, shows the most likely settlement value at the peak and the diminishing chance of extreme settlement values at the tails.

The Gaussian distribution function is used to simulate the distribution of settlements surrounding the tunnel perimeter in the context of tunneling. The function takes into consideration a number of variables that affect settlement behavior, including ground conditions, tunnel depth, building techniques, and soil characteristics. Engineers can determine the projected settlement profile and evaluate the possible effects on surface structures, utilities, and the environment by employing mathematical modeling approaches.

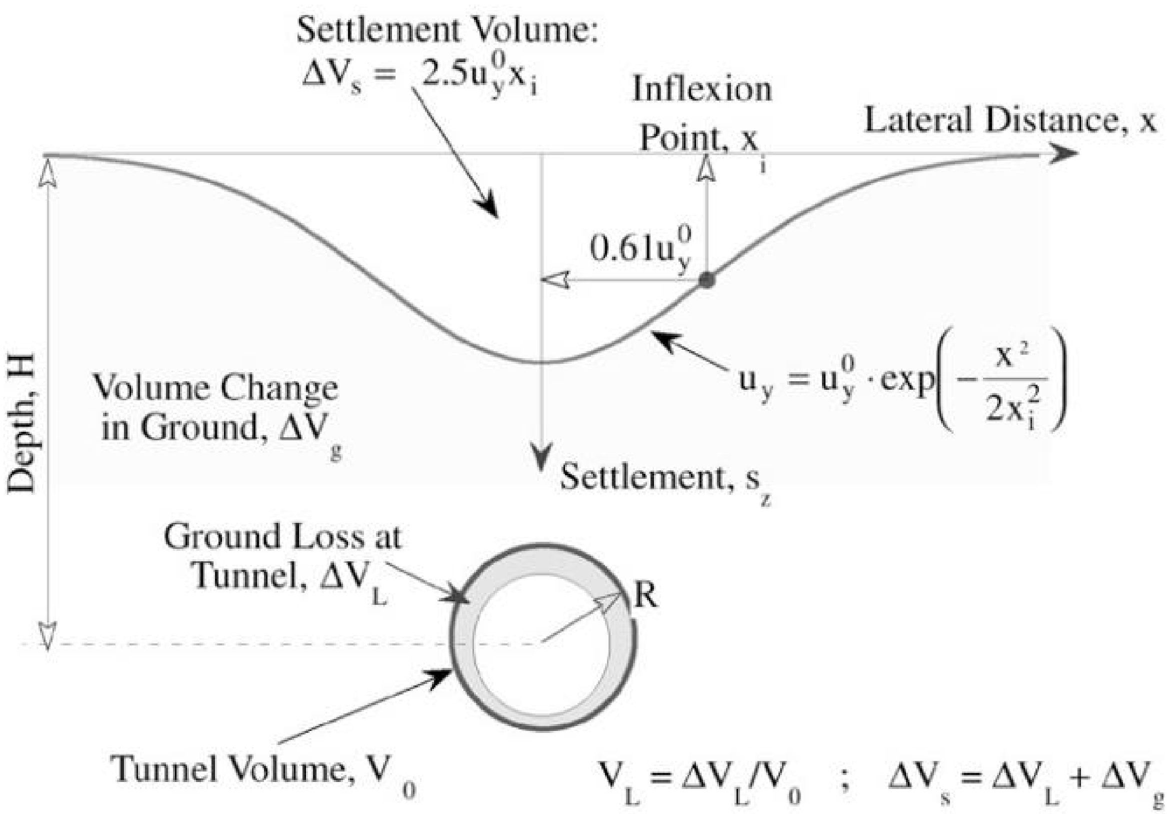


Figure 20. Transversal surface settlement trough's empirical function (Peck, 1969)

3.5.3.3 Numerical Method

Numerical techniques are essential in mechanized tunneling because they may be used to analyze the risk of settlements, or the sinking of the ground surface above or next to a tunnel excavation. A number of things, such as shifting groundwater, deformation of the rock or soil, and building operations, can cause settlements. With the use of numerical techniques, engineers can effectively simulate and forecast settlement behavior, evaluating any hazards and putting suitable mitigation measures in place.

Finite element analysis (FEA) is a popular computational technique for settlement risk assessments. In FEA, the surrounding structures and the ground are divided into discrete parts, each of which represents a tiny part of the entire system. FEA computes the stress, strain, and deformation of the ground and structures under various loading situations, such as TBM excavation or the installation of ground support systems, by applying mathematical equations to these elements.

The finite difference method (FDM) is another numerical technique used in settlement risk analysis. With FDM, the ground is discretized into a grid of finite elements, and at each grid point, differential equations describing the ground's behavior are numerically solved. When modeling transitory events, such the time-dependent settlement reaction to building operations, this technique is especially helpful.

Additionally, depending on the particulars of the tunneling project and the complexity of the ground behavior, several numerical approaches, such as the distinct element method (DEM) or boundary element method (BEM), may also be used.

Numerical approaches allow engineers to model different building scenarios and evaluate their possible effects on ground settlements in settlements risk assessments. The precision of the simulations and the prediction power of the models may be improved by engineers by calibrating the numerical models using field measurements and monitoring data. In the end, numerical techniques offer insightful information on settlement risk that helps engineers create efficient ground support systems, maximize building timelines, and reduce the possibility of unfavorable impacts on the environment and nearby infrastructure.

3.6 Risk for Long and Deep Tunnels - Jamming

The possibility of jamming poses a serious concern in the complex world of automated tunneling, since it can cause delays and disturb the delicate dance of excavation. Tunnel Boring Machines (TBMs) jam when they run into unanticipated obstructions or malfunctions that prevent them from operating smoothly. These barriers can take many different forms: from obstinate stones stuck in rock formations to abrupt changes in the geological environment, such faults or unstable terrain. Operational problems, such as broken equipment or poor maintenance, increase the risk and might result in expensive downtime and troublesome logistics.

Jamming has considerably more consequences than just being inconvenient. Jammed TBM delays generate delays in project timeframes that frequently lead to monetary losses and disagreements over contracts. Furthermore, the complex procedure of freeing a stuck TBM necessitates careful planning and execution, using valuable time and resources that might be better used elsewhere. Safety concerns are also very important since removing a stuck TBM involves dangers to the surrounding infrastructure and onsite workers.

Understanding tunnel deformation and support system response is frequently accomplished through the use of ground reaction curves or the convergence confinement approach. (Hoek E, 1981) In addition, there are several formulations, and the variations are related to the models of elasto-plastic behavior and yield criteria that are employed, as well as the consideration of support systems (such as shotcrete, steel ribs, rock bolts, and concrete lining). (Ömer Aydan, 2019)

A multifaceted strategy is necessary to reduce the danger of jamming as much as possible. Before beginning any excavation, thorough geological surveys and ground investigations offer priceless information about possible obstacles, enabling project teams to foresee and get ready for any difficulties. Furthermore, reliable maintenance procedures and real-time monitoring systems are essential for seeing early warning indicators of approaching jams and taking preventative action before problems worsen. In order to ensure prompt and efficient action in the case of a jamming occurrence, engineering teams, contractors, and stakeholders must work together to build contingency plans and reaction methods. Stakeholders may protect project progress, prevent delays, and maintain the safety and integrity of mechanized tunneling operations by proactively addressing the danger of jamming.

The total force needed for excavation, the backup's pulling force, the force needed to balance the support pressure, and the force needed to overcome the frictional force on the shield is approximated to be the thrust force needed for continuous excavation.

The following is an estimate of the necessary thrust force:

$$F_{required} = F_{boring} + F_{friction} + F_{pulling} + F_{support}$$

$$F_{boring} = F_{n,cutter} \cdot n_{cutter}$$

$$F_{friction} = F_{f,weight} + F_{f,gap}$$

$$F_{f,weight} = W_{TBM} - F_{buoyancy}$$

$$F_{buoyancy} = \gamma_w \cdot A_{face} \cdot L_{shield}$$

$$F_{support} = A_{face} \cdot p_s$$

$F_{friction} = F_{f,weight} + F_{f,gap} F_{f,weight} = W_{TBM} - F_{buoyancy} F_{buoyancy} = \gamma_w \cdot A_{face} \cdot L_{shield}$ where:

- F_{boring} is the force needed for the excavation only during continuous excavation, and $F_{n,cutter}$ is the assumed thrust force per cutter n_{cutter} is the number of cutters

- $F_{pulling}$ is the pulling force of the backup

- $F_{support}$ is the force needed for balancing the support pressure, A_{face} is the area of the excavation face and p_s is the support pressure at the tunnel axis

- $F_{friction}$ is the force needed for overcoming the frictional force on the shield due to ground load resulting from FEM or analytical analyses**.** The frictional force is estimated by multiplying the ground load acting on the shield by the same (for comparison purpose) skin friction coefficients shield-ground μ

  - 0.40 for continuous excavation and no lubrication of the shield.
  - 0.50 for restart after standstill and no lubrication of the shield.
  - 0.15 for continuous excavation and lubrication of the shield.
  - 0.25 for restart after standstill and lubrication of the shield.

The requirement to "restart after standstill" is solely predicated on adopting a higher skin friction coefficient (μ) value (static friction as opposed to dynamic friction), taking technical literature information into consideration. $F_{buoyancy}$ is the buoyancy force acting at the bottom of the TBM; L_{shield} is the total length of the shield, γ_w is the unit weight of the water. On the safe side, it is neglected.

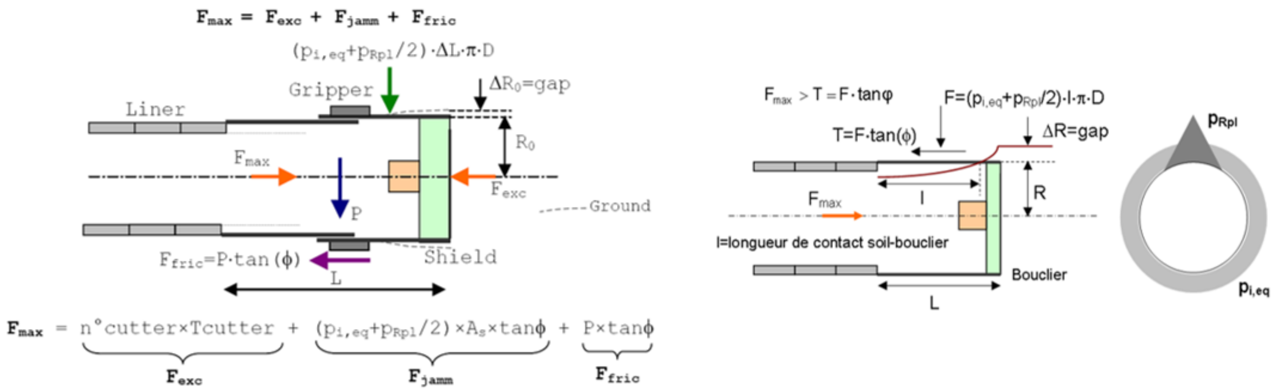


Figure 21. Basic scheme for implementation of TBM jamming analytical calculation.

3.6.1 Analysis of Axial-symmetric FEM

To comprehensively address the risk of jamming in mechanized tunneling, a sophisticated approach integrating advanced numerical modeling techniques is essential. One such method, the axial-symmetric Finite Element Method (FEM) analysis, offers a comprehensive assessment of the intricate interactions between the Tunnel Boring Machine (TBM) and the surrounding geological strata. By creating virtual replicas of the excavation process, axial-symmetric FEM models accurately simulate the distribution of forces, stresses, and displacements within the rock mass surrounding the tunnel. This enables engineers to identify potential trouble spots, such as zones of high stress or instability, which could elevate the risk of jamming.

The axial-symmetric FEM analysis allows engineers to evaluate various factors influencing jamming susceptibility, including geological conditions, the effectiveness of ground support measures, and operational parameters of the TBM. By systematically adjusting these parameters and conducting sensitivity analyses, engineers can assess critical factors impacting jamming risk and optimize excavation strategies accordingly.

Furthermore, the axial-symmetric FEM approach facilitates the exploration of mitigation techniques aimed at reducing jamming risk. Engineers can simulate the implementation of different ground support systems, such as shotcrete or rock bolts, to assess their effectiveness in stabilizing the excavation face and minimizing the likelihood of jamming events. Additionally, by integrating real-time monitoring data from instruments installed on the TBM and along the tunnel, engineers can validate the accuracy of numerical models and enhance predictive capabilities.

To investigate the TBM-ground interaction during excavation and standstills, incremental small strain evaluations using axisymmetric FEM models are conducted. While these analyses make certain simplifying assumptions, such as homogeneous and isotropic ground and uniform initial stress and hydraulic head fields, they provide valuable insights into the complex dynamics of TBM excavation and assist in optimizing risk management strategies for mechanized tunneling projects.

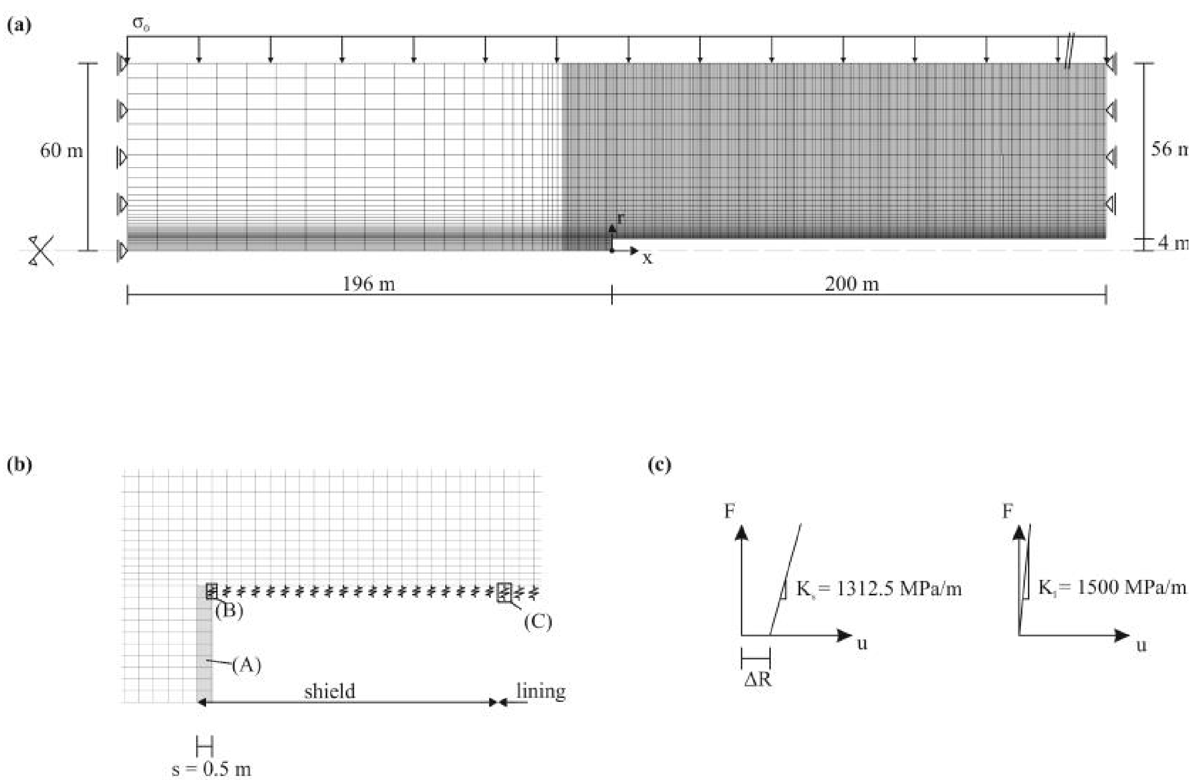


Figure 22. FEM model – Geometry, mesh, and boundary conditions(a &b) (Anagnostou)

Ground Model

In the ground model employed for the analysis, the rock mass is discretized using four-noded rectangular solid elements, allowing for the representation of the rock as a continuous medium. This discretization enables engineers to simulate the mechanical behavior of the ground with a high level of accuracy and detail. The chosen material model assumes linear elasticity coupled with complete plasticity, reflecting the complex response of the rock mass under varying loading conditions. The Mohr-Coulomb yield criteria and a non-associated flow rule are utilized to capture the non-linear behavior of the material, accounting for factors such as shear strength and dilation. By incorporating these advanced constitutive models into the ground model, engineers can accurately simulate the response of the rock mass to the forces and stresses imposed by the tunneling process, thereby facilitating a comprehensive analysis of potential risks such as jamming events.

Limitations

In the coupled analysis (undrained), certain assumptions are made to facilitate the simulation process. These assumptions include setting the y-displacement to zero at the lateral limits, ensuring that the x-displacement is zero at the axisymmetric axis, and imposing uniform pressure on top of the model equal to the original total stress in the ground. Additionally, specific hydraulic boundary conditions are applied, such as maintaining the total pressure equal to the initial pore water pressure in the ground on top of the model and enforcing zero water flow through the lateral boundaries and the axisymmetric axis. Mixed flow conditions are considered at the tunnel face, allowing water to flow from the ground into the tunnel while restricting flow in the opposite direction to maintain realism.

For the effective stress mechanical analysis (drained), different assumptions are made to capture the drained response of the ground. Here, mechanical boundary conditions dictate a uniform pressure equivalent to the initial effective stress in the ground on top of the model, with zero x-displacement at the axisymmetric axis and zero y-displacement at the lateral borders. These assumptions provide a framework for conducting the analysis, allowing engineers to simulate the behavior of the rock mass under various loading and boundary conditions and assess the risk of jamming events during mechanized tunneling operations.

Structural Element Modeling

In structural element modeling, a sophisticated approach is adopted to accurately represent the interaction between various components involved in mechanized tunneling. Radial springs are employed as a means

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to simulate both the segmental lining and the Tunnel Boring Machine (TBM) shield. These radial springs serve as effective proxies for the structural elements, allowing engineers to capture their behavior within the numerical model.

One of the critical aspects addressed in the modeling process is the intricate interaction between the TBM shield and the surrounding ground. This interaction encompasses several factors, including the initial gap between the ground and the shield, the support provided to the tunnel wall by pressurized slurry in cases where an open gap exists, and the support offered by the shield itself when the gap is closed. To accurately simulate these complex dynamics, non-linear springs, commonly referred to as shield springs, are integrated into the model. These shield springs are designed to exhibit non-linear behavior, enabling them to adequately represent the varying levels of support and interaction between the TBM shield and the surrounding ground throughout the excavation process.

By incorporating radial and non-linear springs into the structural element modeling, engineers can effectively simulate the intricate behavior of the segmental lining and the TBM shield during tunnel excavation. This level of detail allows for a comprehensive analysis of the interaction between these components and the surrounding ground, facilitating a more accurate assessment of potential risks, such as jamming events, and enabling the development of robust mitigation strategies to enhance the safety and efficiency of mechanized tunneling operations.

The following equations explain the constitutive model of the shield springs:

$F_s = F_o \qquad \text{for } u < \Delta R$

$F_s = -K_{sf} * (u - \Delta R) + F_o \qquad \text{for } u > \Delta R$

where:

$F_o = A_s * p_s$

$A_s = 2 * \pi * R_s * x_s$

$K_s = \frac{E_s * d_s}{{R_s}^2}$

$K_{sf} = K_s * A_s$

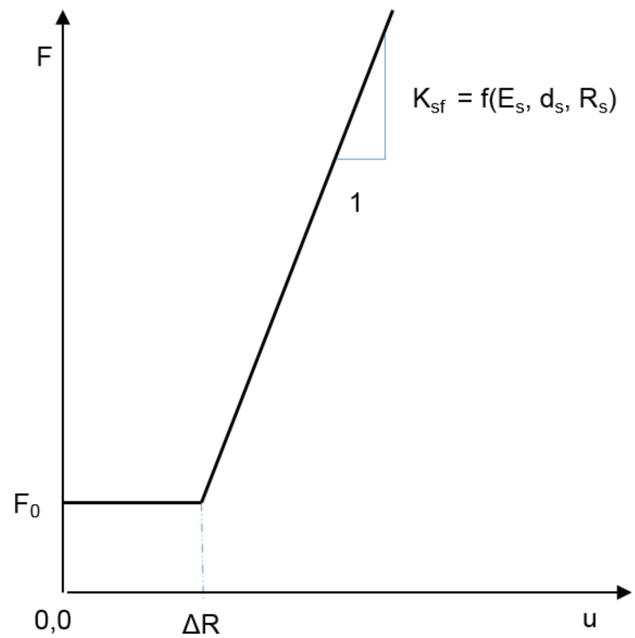

Figure 23. Curve of force –displacement of the shield springs

To simulate the lining, linear springs, also known as lining springs, were employed. The following equation describes the constitutive model of the liner springs:

$F_l = - K_{lf} * u$

where:

$K_{lf} = K_l * A_l$

$K_l = \frac{E_l * \ d_{sl}}{{R_l}^2}$

$A_l = 2 * \pi * R_l * x_s$

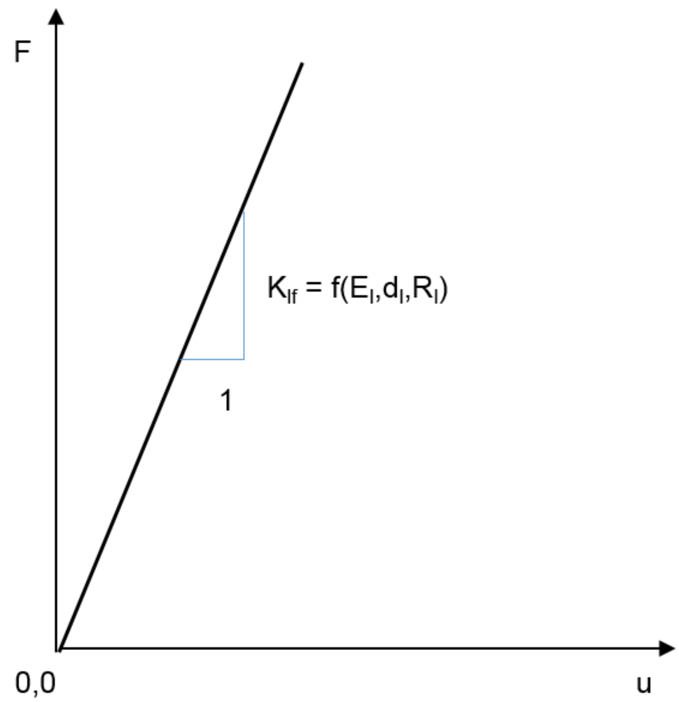

Figure 24. Curve of force –displacement of the lining springs

All things considered, the examination of axial-symmetric FEM models for jamming risk assessments is a highly developed and indispensable instrument in the toolbox of tunneling engineers. Engineers may improve the safety, effectiveness, and performance of mechanized tunneling projects by proactively identifying and mitigating jamming concerns by utilizing the insights obtained from these models.

3.6.2 Time-dependent Behavior of the Ground and Analytical Evaluation

Squeezing is a time-dependent significant deformation that happens around a tunnel and reduces the tunnel cross-section, according to the International Society of Rock Mechanics (ISRM). (Jian-Zhi Zhang, 2017)

When evaluating the danger of jamming in mechanized tunneling operations, it is essential to comprehend the time-dependent behavior of the earth. Over time, a variety of variables, including stress redistribution, creep, and the expansion or consolidation of the surrounding soil or rock mass, affect the ground conditions. The possibility of jamming accidents and the stability of the excavation face can both be strongly impacted by these time-dependent phenomena. By using sophisticated analytical approaches to simulate and anticipate ground deformations and responses to excavation activities over long periods of time, it is possible to analyze the time-dependent behavior of the ground.

The use of mathematical models based on soil mechanics and structural engineering concepts is one method for analytically assessing jamming risk analysis. To determine the likelihood of jamming, these models take into account variables including the ground's mechanical characteristics, TBM specifications, and operational circumstances. Creating equations or methods that explain the relationship between the TBM and the surrounding ground while accounting for variables like ground stress, TBM thrust, and cutterhead torque is a common task for analytical assessments. Through analytical solution of these equations, engineers are able to determine the important components that contribute to jamming susceptibility and estimate the risk of jamming under various circumstances.

Moreover, probabilistic techniques are frequently used in analytical assessments of jamming risk analysis to take into consideration the inherent uncertainties in TBM operation and ground conditions. With probabilistic techniques, several outputs are evaluated according to statistical distributions of input factors, including excavation geometry, TBM performance, and ground strength. When deciding on risk mitigation techniques and contingency planning, engineers may make well-informed judgments by taking into account the range of possible outcomes and their corresponding probabilities.

All things considered, the analytical assessment of jamming risk analysis, supported by knowledge of the ground's time-dependent behavior, offers insightful information about the intricate relationships between the TBM and its surroundings. Engineers may evaluate jamming risk more accurately and confidently by using probabilistic methodologies and advanced analytical tools, which will eventually improve the efficiency and safety of mechanized tunneling operations.

The primary cause of the ground's time-dependent behavior is the process of creep and consolidation occurring in the tunnel's vicinity. These activities occur concurrently with the face advance-induced spatial stress redistribution at the tunnel face. The rheological behavior of the earth is linked to creep, which is more noticeable under extremely stressful circumstances. Consolidation occurs when digging a tunnel through a water-bearing area. For a low-permeability ground, consolidation is a source of time-dependency. It is connected to the temporary seepage flow process that the tunnel's excavation causes. Squeezing is linked to plastic yielding and overstressing of the ground, which often results in a rise in volume (plastic dilatancy).

Squeezing raises the water content of the ground if it is saturated. The rate at which this happens varies according to how permeable the ground is. In the near run, the water content in a low-permeability ground stays constant. Negative excess pore pressures are produced by the excavation process because the pore water prevents dilatancy. A temporary seepage flow process begins to form in the direction of the tunnel since they are higher there than they are farther away. Over time, the negative surplus pore pressure dissipates, causing further time-dependent deformations and a change in the effective stresses. Over time, the load operating on a shield or liner that prevents ground deformation will rise.

Regarding the temporary process, two key states can be identified: the immediate post-excavation state, which is defined as the undrained conditions due to its constant water content; and the long-term state, which is determined by the steady state pore pressure distribution, also known as the drained conditions. The ratio of advance rate v to ground permeability k controls the time-dependent development of ground deformations.

Undrained conditions will predominate in the machine area if this ratio is large, as would be the case with fast excavation through a low-permeability ground. Conversely, drained conditions will develop nearly right away following excavation if the excavation moves slowly or if the ground permeability is great (low v/k ratio).

Different analyses in drained and undrained situations were conducted based on these concepts.

Type 1: To simulate undrained circumstances, total stress/mechanical analyses in total stresses with undrained parameters were performed.

Type 2: To simulate TBM progress, total stress/mechanical analyses in effective stresses were performed without taking groundwater into consideration.

Type 3: In order to take into account, the problem's time dependence during both advance and standstill low-permeability ground, coupled hydraulic-mechanical studies with effective parameters were carried out. The analysis of these analyses' results is ongoing; it is not presented in this paper.

Type 4: To simulate TBM progress through low permeability ground, coupled hydraulic-mechanical studies with effective parameters, mechanical pore pressure production, and no flow were performed.

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Pore pressures were accounted for in the coupled study by modeling the ground as a saturated porous medium using the effective stress theory. Darcy's law serves as a model for seepage flow. It has been presumed that incompressible ground components exist because, in the case of highly deformable weak rocks, the impact of the solid grains' or pore water's compressibility is minimal.

It is only when the overcut is closed that the squeezing rock begins to apply pressure to the shield. The mixed boundary condition can be interpreted as follows, assuming a linear connection between the squeezing loads and the shield deformation. (Ramoni M. A., 2010)

$$p_i(y,t) = \begin{cases} 0 & \text{if} \quad u_r(y,t) - u_f \leqslant \Delta R \\ K_s\,[u_r(y,t) - u_f - \Delta R] & \text{if} \quad u_r(y,t) - u_f > \Delta R \end{cases}$$

where $u_r(y, t)$ indicates the radial displacement along the longitudinal direction, u_f indicates the pre-deformation of the rock formation occurring ahead of the tunnel face and before excavation, ΔR indicates the radial gap around the shield, and K_s indicates the stiffness of the shield, which is given by (Ramoni M. L., 2011)

$$K_s = \frac{E_s d_s}{R_0^2}$$

where the shield's thickness (d_s) and Young's modulus (E_s) are, respectively,

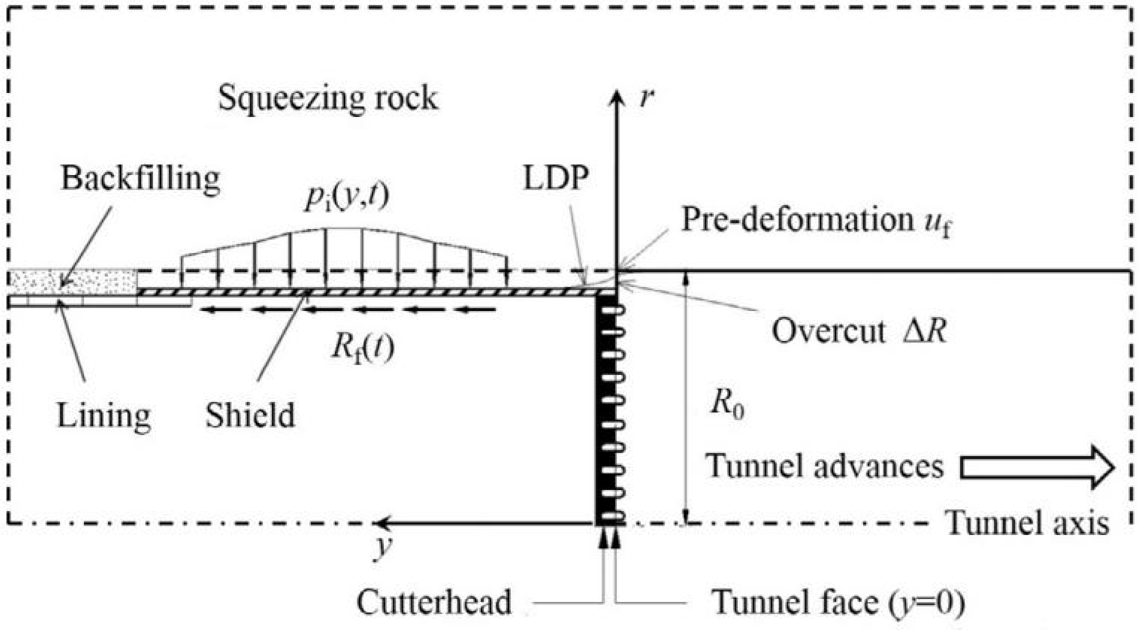

Figure 25. Problem Layout (Jian-Zhi Zhang, 2017)

3.6.3 Mitigation Measures

Measures to Lower the Forces TBM Geometry is Acting on the Shield

Mitigation measures aimed at reducing the forces exerted by the Tunnel Boring Machine (TBM) geometry on the shield play a crucial role in enhancing the safety and efficiency of mechanized tunneling operations. One such measure involves implementing strategies to increase the over-excavation, which has been shown to have a beneficial impact on the contact pressures and ground tensions acting on the shield. By introducing further over-excavation, the pressures exerted on the shield can be effectively mitigated.

To achieve this, the primary drive repositioning system is equipped with a maximum lift of 50mm, allowing for adjustments to the eccentricity to facilitate over-excavation. However, it's important to note that based on current data, there appears to be no significant correlation between extensive over-excavations and increased eccentricity. Therefore, it's essential to carefully evaluate the potential outcomes of additional over-excavation measures to ensure their effectiveness.

While increasing over-excavations may help alleviate pressure on the shield, it's crucial to consider potential challenges that may arise. Larger annular gaps resulting from greater over-excavations can pose difficulties in controlling machine guidance, profiling in the lower regions of the head scrapers, and executing proper backfilling grout injections at the contour. Moreover, it's essential to acknowledge that these solutions may only be effective under regular excavation circumstances and may not suffice in the event of extended machine stoppage due to the stress trend observed in time-dependent models.

In conclusion, while implementing measures to increase over-excavations holds promise for reducing forces exerted on the shield during mechanized tunneling, careful consideration of potential challenges and limitations is essential to ensure the effectiveness and safety of these mitigation strategies. By balancing risk reduction with operational feasibility, tunneling projects can enhance their resilience to TBM geometry-related forces and optimize overall project outcomes.

Ground Condition Improvement

Ground condition improvement plays a pivotal role in ensuring the stability and efficiency of tunneling operations, especially in challenging geological conditions. Pre-grouting interventions offer a proactive approach to enhance ground reactivity during excavation, leveraging geotechnical characterization data to determine the most suitable grouting strategy. However, it's essential to assess the permeability characteristics of the ground to evaluate the effectiveness of grout injection and ensure optimal results.

In addition to pre-grouting, active drainage systems represent another valuable tool for ground improvement. Implementing active drainage measures ahead of excavation, as well as maintaining drains throughout TBM advance, can significantly mitigate potential ground instability risks. These drainage systems utilize suitably sized housings and connections integrated into the segmental lining, allowing for the continuous removal of excess water and pressure buildup during excavation.

The effectiveness of active drainage systems is further enhanced through the use of Blow-Out Preventers (BOP), which serve as crucial safety mechanisms to prevent excessive water ingress and pressure surges. By actively managing groundwater levels and pressures, these drainage systems contribute to maintaining a stable excavation environment, reducing the likelihood of ground-related hazards such as collapses or excessive settlements.

Overall, the combination of pre-grouting interventions and active drainage systems represents a comprehensive approach to ground condition improvement in mechanized tunneling. By proactively addressing potential geological challenges and implementing effective mitigation measures, tunneling projects can enhance safety, optimize excavation efficiency, and minimize the risk of ground-related disruptions.

4. Risk Assessment and Mitigation Strategies

4.1 Evaluation of Numerical Simulation Results on Risk Assessment

Regarding risk assessment and mitigation techniques for urban mechanized tunneling projects, the assessment of numerical simulation findings is essential to comprehending possible dangers and formulating efficient mitigation solutions. Engineers may simulate different situations, evaluate the behavior of impacts caused by tunneling, and estimate the related dangers to structures and infrastructure by using numerical models.

The process of assessing numerical simulation findings starts with a thorough examination of the data produced by the models, which includes earth movements, structural reactions, and any risks to nearby structures. To find possible weak points and areas of concern, this entails closely examining variables including stress distributions, vibration levels, and patterns of ground settlement.

Engineers also use real-world observations and empirical data to compare simulated results with simulation models in order to evaluate the correctness and dependability of the models. The process of calibrating and validating simulation models serves to guarantee that the intricate relationships between tunneling operations, surrounding structures, and ground conditions are faithfully portrayed. This improves the trustworthiness of the results of risk assessments.

Engineers study the results of numerical simulations in detail before determining the dangers to infrastructure and buildings. This means determining possible failure mechanisms, evaluating the possibility and effects of unfavorable occurrences, and ranking risks according to their importance and possible influence.

Engineers create and implement focused mitigation solutions to reduce identified risks and protect infrastructure and buildings based on the results of the risk assessment. These tactics might consist of:

- Structural reinforcement is the process of fortifying a building's structure by bracing, underpinning, or retrofitting it to increase its resistance to ground movements and reduce possible damage.
- Ground Improvement Measures: Applying measures to maintain soil conditions and reduce ground settlement at tunneling sites, such as grouting, soil stabilization, or ground freezing.
- Installing vibration isolation systems, dampening equipment, or protective barriers can help reduce the vibrations that neighboring buildings and sensitive equipment feel during tunneling operations.
- Using monitoring tools to continually observe ground movements, structure reactions, and environmental data, such as tilt meters, strain gauges, and seismographs, can help identify any hazards early and take appropriate action.
- Creating emergency response plans and contingency plans in order to handle unanticipated occurrences or emergencies, including building evacuations, service outages, or structural problems, and lessen their effects, is known as contingency planning.

Engineers can effectively manage the risks associated with mechanized tunneling projects in urban areas by applying targeted mitigation strategies and rigorously evaluating numerical simulation results. This ensures the sustainability, resilience, and safety of buildings and infrastructure in the built environment.

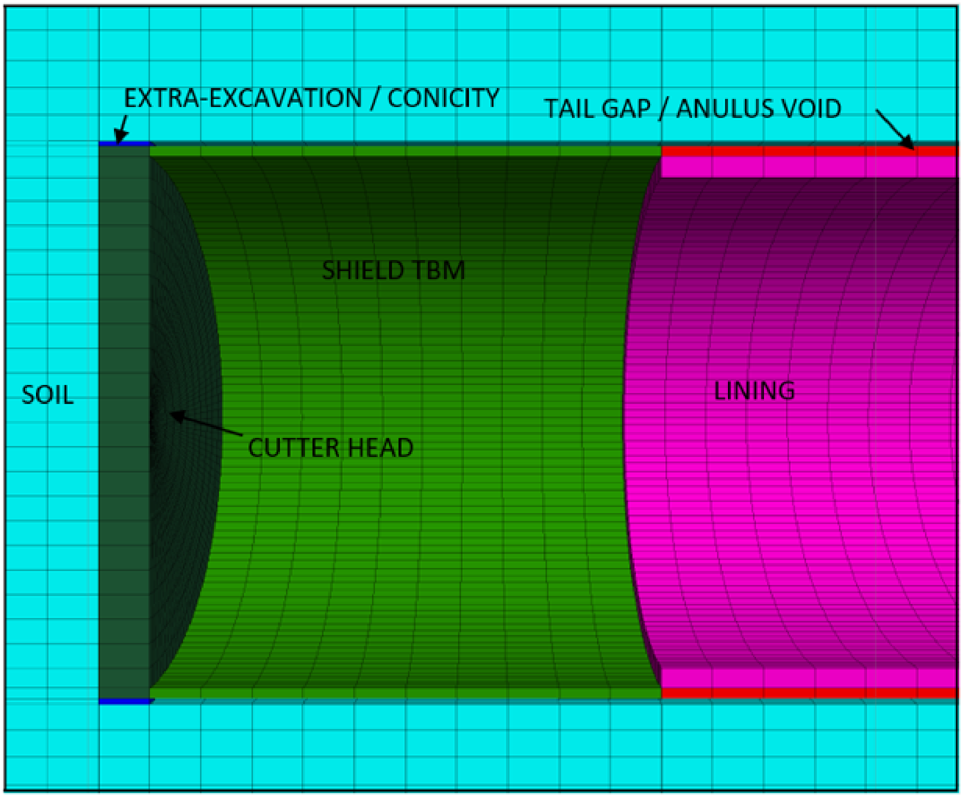

Figure 26. Labeled Numerical Analysis of Tunnel Boring Machine in Underground

Evaluating how vertical displacement and distance from the tunnel axis relate to one another is essential for determining how tunneling operations may affect nearby structures. As one gets farther away from the tunnel axis, the vertical displacement usually decreases, according to a well-known pattern. However, the precise behavior may differ based on variables including the composition of the soil, the depth of the tunnel, the construction process, and the structural features of nearby structures.

The vertical displacement tends to be most noticeable around the tunnel axis, where excavation-induced stress concentrations are at their largest. Because of this, depending on the kind of ground and the direction of tunneling-induced deformations, structures along the tunnel axis may undergo considerable uplift or settlement. This can have negative consequences that put the integrity of the structure and the safety of its occupants at risk, such foundation movement, structural deformation, and cracking.

Because the effects of stress and strain caused by tunneling are attenuated, the amplitude of vertical displacement usually decreases with increasing distance from the tunnel axis. Structures that are positioned at a greater distance from the tunnel axis are less vulnerable to the direct effects of excavation operations, undergoing only slight or insignificant vertical displacement. However, depending on the particular geotechnical conditions and building characteristics, some degree of settling or ground movement may still occur even at higher distances, albeit to a smaller level.

Numerical modeling and field monitoring tools are frequently used to quantify the connection between vertical displacement and distance from the tunnel axis. Engineers can forecast the distribution of vertical displacement surrounding tunneling excavations and evaluate its variation with distance using numerical simulations, such as finite element analysis (FEA) or finite difference method (FDM). In order to evaluate real ground movements and verify numerical forecasts, field monitoring entails installing monitoring devices at varying distances from the tunnel axis, such as extensometers, inclinometers, or settlement markers.

Comprehending the correlation between vertical displacement and distance is imperative in evaluating the possible hazards to edifices and infrastructure in the vicinity of tunneling endeavors and in formulating suitable remedial strategies. Through the quantification of vertical displacement's extent and geographical distribution, engineers are able to assess the impacts on structures, pinpoint regions of vulnerability, and execute specific procedures aimed at mitigating negative consequences and safeguarding the safety and structural integrity of the built environment.

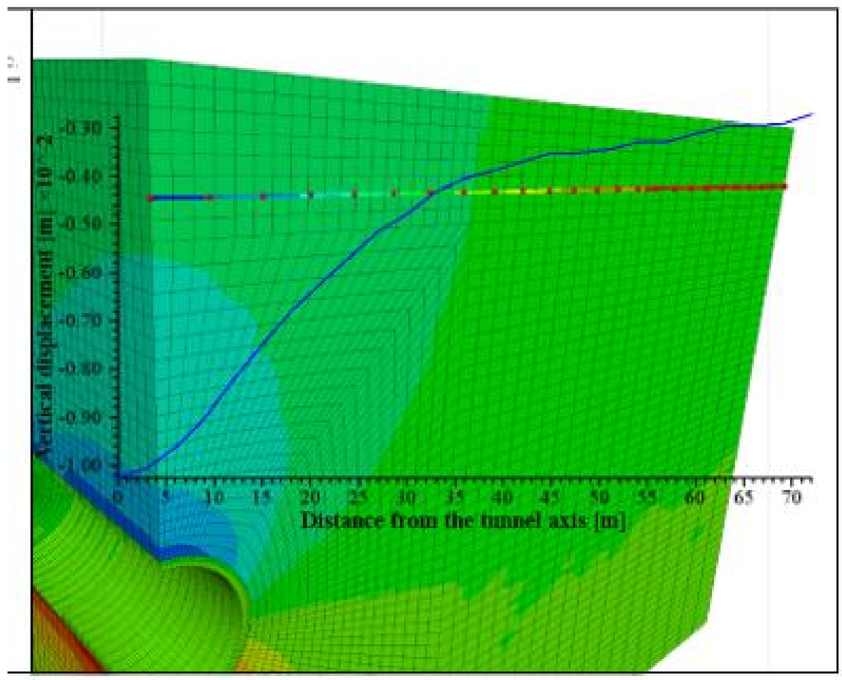

Figure 27. Shallow Tunnel Vertical Displacement Based on the Distance from the Tunnel Axis

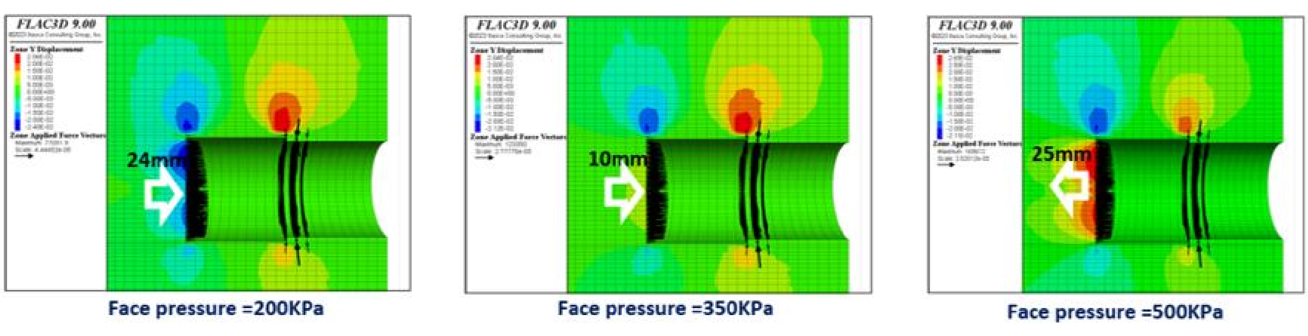

Figure 28. Face Pressure Impact

4.2 Proposal of Risk Mitigation and Control Strategies

To reduce possible dangers and protect buildings, infrastructure, and the surrounding environment, it is crucial to provide appropriate risk reduction and management measures in the context of automated tunneling projects in urban environments. The following are a few crucial tactics that might be suggested: Pre-construction Surveys and Monitoring: To evaluate the state of the infrastructure, utilities, and existing structures surrounding the tunneling site, conduct thorough pre-construction surveys. Throughout the project lifespan, implement continuous monitoring programs to detect ground movements, structure reactions, and environmental factors utilizing modern monitoring technology including tilt meters, extensometers, and vibration sensors.

Ground Improvement Techniques

Ground improvement techniques play a vital role in mitigating risks associated with tunneling projects by stabilizing soil conditions and minimizing ground settlement. These techniques involve various methods aimed at enhancing the strength and stability of the soil surrounding the tunneling sites.

One effective method is jet grouting, which involves injecting high-pressure grout into the ground to create a solid, impermeable mass. This technique is particularly useful in areas with unstable or soft soils, as it improves soil strength and reduces the risk of settlement by creating a reinforced soil matrix.

Another approach is deep soil mixing, where cementitious or lime-based materials are injected into the ground and mixed with the existing soil using specialized equipment. This process strengthens the soil and increases its load-bearing capacity, making it more resistant to settlement and deformation caused by tunneling activities.

Grouting is also commonly used to stabilize soil conditions around tunneling sites. This technique involves injecting grout into the ground to fill voids, consolidate loose soil, and improve soil cohesion. By enhancing the properties of the surrounding soil, grouting helps minimize ground movement and settlement, thereby protecting nearby infrastructure and buildings.

Soil nailing is another effective ground improvement method that involves installing steel or fiberglass rods (nails) into the ground at regular intervals and anchoring them with grout or other stabilizing materials. This technique provides lateral support to the soil, preventing it from collapsing or shifting during excavation. Soil nailing is particularly useful in areas with steep slopes or unstable soil conditions.

Overall, applying ground improvement techniques such as jet grouting, deep soil mixing, grouting, and soil nailing can significantly enhance soil stability, reduce ground settlement, and protect nearby infrastructure and buildings from damage during tunneling operations. These methods offer cost-effective and efficient solutions for addressing soil-related challenges in urban tunneling projects, ensuring the safety and integrity of the surrounding environment.

Installing Vibration Isolation Systems

Installing vibration isolation systems is essential for minimizing the adverse effects of tunneling operations on neighboring buildings and sensitive equipment. These systems are designed to mitigate vibrations caused by tunneling activities, thereby reducing the risk of damage and discomfort to nearby structures and occupants.

One approach to vibration isolation involves the use of damping equipment, which absorbs and dissipates vibrational energy to reduce its transmission to surrounding structures. Damping devices such as tuned mass dampers or viscoelastic materials are installed strategically to counteract the vibrations generated by tunneling machinery, preventing them from propagating through the ground and affecting nearby buildings.

Protective barriers are another effective means of reducing vibrations from tunneling operations. These barriers are typically constructed using robust materials such as concrete, steel, or composite panels and are installed between the tunneling site and adjacent structures to block or attenuate the transmission of vibrations. By acting as a physical barrier, these structures help minimize the amplitude and frequency of vibrations reaching nearby buildings and equipment.

Isolation pads are commonly used to isolate sensitive equipment from ground-borne vibrations. These pads, typically made of rubber or elastomeric materials, are placed beneath machinery or equipment to decouple them from the surrounding structure. By isolating equipment from ground vibrations, these pads prevent the transmission of vibrations to nearby buildings and equipment, protecting them from damage and ensuring their proper functioning.

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Additionally, vibration absorbers can be incorporated into the design of structures to dampen vibrations caused by tunneling activities. These devices, which may include tuned mass dampers or tuned vibration absorbers, are tuned to resonate at specific frequencies, effectively canceling out vibrations and reducing their impact on buildings and occupants.

Overall, installing vibration isolation systems such as damping equipment, protective barriers, isolation pads, and vibration absorbers is critical for minimizing the effects of tunneling-induced vibrations on nearby buildings and sensitive equipment. These systems help preserve the integrity of structures, ensure the safety and comfort of occupants, and mitigate the potential risks associated with tunneling operations in urban environments.

Monitoring and Early Warning Systems

Monitoring and early warning systems play a crucial role in ensuring the safety and integrity of tunneling operations in urban environments. These systems consist of a variety of monitoring equipment and sensors deployed throughout the tunneling site to continuously assess ground movements, structure reactions, and environmental conditions. By collecting real-time data, these systems enable engineers and project managers to identify changes in ground conditions and structural behavior, allowing for timely intervention to mitigate potential risks and prevent negative impacts.

One essential component of monitoring systems is tilt meters, which are used to measure changes in the tilt or inclination of the ground surface. Tilt meters are strategically placed at various locations around the tunneling site to detect ground movements that may indicate potential instability or settlement. By continuously monitoring tilt values, engineers can identify any deviations from baseline measurements and take appropriate action to address emerging issues.

Strain gauges are another critical monitoring tool used to measure changes in strain or deformation within structures or components. These gauges are installed on key structural elements such as walls, columns, and beams to monitor their response to tunneling-induced loads and ground movements. By tracking strain levels in real-time, engineers can assess the structural integrity of buildings and infrastructure and identify any signs of distress or damage.

Seismographs are deployed to monitor seismic activity and vibrations generated by tunneling operations. These instruments record ground motion and seismic waves, providing valuable data on the intensity and frequency of vibrations at the tunneling site and surrounding areas. By analyzing seismograph readings, engineers can assess the potential impact of vibrations on nearby structures and equipment and implement measures to minimize their effects.

Geotechnical sensors are used to monitor soil properties and behavior during tunneling operations. These sensors measure parameters such as soil pressure, moisture content, and density, providing insights into ground conditions and stability. By continuously monitoring geotechnical data, engineers can detect changes in soil behavior that may indicate potential hazards such as ground settlement or instability.

Overall, monitoring and early warning systems provide valuable insights into the behavior of the ground and structures during tunneling operations, allowing engineers to proactively identify and address potential risks. By leveraging real-time data from a range of monitoring equipment, project teams can ensure the safety and success of tunneling projects in urban environments while minimizing disruptions and protecting surrounding infrastructure and communities.

Contingency Planning and Emergency Response

Contingency planning and emergency response are critical components of risk management for tunneling projects in urban environments. These plans are designed to address unforeseen situations or crises that may arise during tunneling operations and ensure a coordinated and effective response to protect the safety of workers, the public, and the surrounding environment.

One key aspect of contingency planning is establishing clear lines of communication and protocols for coordination among project stakeholders. This includes defining roles and responsibilities for project team members, emergency services, local authorities, and other relevant parties. By clearly delineating communication channels and procedures for information sharing, project teams can ensure a rapid and coordinated response to emergencies.

Another important element of contingency planning is the development of evacuation protocols and procedures. This involves identifying evacuation routes, assembly points, and emergency shelters for workers and nearby residents in the event of an emergency. Training programs should be conducted regularly to ensure that all personnel are familiar with evacuation procedures and know how to respond effectively in emergency situations.

Additionally, contingency plans should outline strategies for cooperation with emergency services and local authorities. This may include establishing protocols for requesting assistance, providing access to the tunneling site for rescue and recovery operations, and coordinating response efforts with relevant agencies. By fostering collaboration and cooperation with external stakeholders, project teams can enhance the effectiveness of emergency response efforts and minimize the impact of crises.

Contingency planning also involves identifying potential risks and vulnerabilities associated with tunneling operations and developing mitigation measures to address them. This may include measures such as installing emergency ventilation systems, implementing emergency shutdown procedures for tunneling equipment, and stockpiling emergency supplies and equipment. By proactively identifying and addressing potential risks, project teams can reduce the likelihood of emergencies and enhance the resilience of tunneling operations.

Overall, contingency planning and emergency response are essential components of risk management for tunneling projects. By developing comprehensive plans and protocols for responding to emergencies, project teams can minimize the impact of crises and ensure the safety and success of tunneling operations in urban environments.

Community Engagement and Public Outreach

Community engagement and public outreach play a vital role in tunneling projects, ensuring transparency, fostering trust, and promoting collaboration among stakeholders. These initiatives involve active interaction with a diverse range of individuals and groups, including building owners, residents, businesses, community organizations, and local authorities. The primary objectives of community engagement and public outreach are to provide information, address concerns, and facilitate meaningful participation in the decision-making process regarding tunneling projects.

One of the key elements of community engagement is to provide stakeholders with accurate and timely information about the tunneling project. This includes sharing details about the project's objectives, scope, timeline, and potential impacts on the surrounding area. Through open forums, public meetings, and informational sessions, project teams can communicate project updates, address questions and concerns, and solicit feedback from the community.

In addition to providing information, community engagement efforts aim to actively involve stakeholders in the decision-making process. This may involve seeking input on project design alternatives, mitigation measures, and other aspects of the project that may affect the community. By soliciting input from a diverse range of stakeholders, project teams can identify potential concerns and preferences early in the planning process and incorporate them into project planning and design.

Furthermore, community engagement initiatives provide an opportunity to educate stakeholders about risk mitigation and control techniques associated with tunneling projects. Through workshops, seminars, and outreach programs, project teams can raise awareness about the measures being implemented to minimize potential risks and ensure the safety of the community. By promoting understanding and cooperation, project teams can build trust and credibility within the community and foster a collaborative approach to project implementation.

Overall, effective community engagement and public outreach are essential for building positive relationships, promoting transparency, and achieving successful outcomes in tunneling projects. By actively engaging with stakeholders, listening to their concerns, and incorporating their input into decision-making processes, project teams can enhance project acceptance, minimize conflicts, and ultimately contribute to the overall success of the project.

Regulatory Compliance and Permission

Regulatory compliance and obtaining necessary permissions are critical aspects of tunneling projects to ensure adherence to legal requirements and mitigate potential risks to structures, infrastructure, and the environment. Compliance involves aligning tunneling operations with relevant rules, regulations, codes, and permit requirements established by local, regional, and national regulatory bodies. The following steps outline key components of regulatory compliance and permission acquisition in tunneling projects:

Permit Acquisition: Obtaining permits and approvals from regulatory agencies is essential before initiating tunneling operations. This may include permits for construction, excavation, environmental impact assessments, noise and vibration mitigation, traffic management, and any other activities that may affect public safety or the environment. Project teams must submit comprehensive permit applications detailing project plans, designs, mitigation measures, and environmental management strategies to obtain necessary approvals.

Environmental Assessments: Conducting environmental assessments is a crucial step in regulatory compliance to evaluate the potential environmental impacts of tunneling activities. Environmental assessments may include studies on air quality, water quality, noise pollution, habitat disturbance, and other factors. Project teams must adhere to environmental regulations and standards, implement mitigation measures to minimize adverse impacts, and obtain clearance from environmental regulatory agencies before commencing construction.

Compliance with Industry Standards: Tunneling projects must adhere to industry standards, guidelines, and best practices to ensure safe and efficient operations. These standards may cover aspects such as tunnel design, construction methods, materials, equipment specifications, and safety protocols. By following established industry standards, project teams can enhance project quality, reliability, and safety while minimizing risks to workers, the public, and the environment.

Risk Assessment and Management: Regulatory compliance involves conducting comprehensive risk assessments to identify potential hazards, evaluate risks, and implement appropriate risk management measures. This may include assessing geological conditions, structural integrity, ground stability, seismic risks, and other factors that may affect tunneling operations. By addressing identified risks through mitigation measures and contingency plans, project teams can minimize the likelihood of accidents, injuries, and environmental damage.

Monitoring and Reporting: Regulatory compliance also entails implementing monitoring programs to track project activities, assess environmental impacts, and ensure compliance with permit conditions and regulatory requirements. Project teams must regularly monitor construction activities, ground movements, environmental parameters, and other relevant factors, and report findings to regulatory agencies as required. Timely reporting enables regulatory authorities to assess project compliance and take corrective action if necessary.

By ensuring regulatory compliance and obtaining necessary permissions, tunneling projects can proceed in a manner that minimizes risks, protects public safety and the environment, and complies with legal requirements. Collaboration with regulatory agencies, stakeholders, and communities is essential throughout the project lifecycle to address concerns, address issues, and ensure successful project outcomes.

Through the proactive and well-coordinated implementation of risk mitigation and control measures, tunneling projects may successfully manage possible hazards and limit negative effects on buildings, infrastructure, and the urban environment. The joint objective of guaranteeing the safety, resilience, and sustainability of urban infrastructure and the built environment necessitates strong cooperation amongst project stakeholders, including engineers, contractors, regulators, and the community.

5. Conclusion

In conclusion, this thesis offers a comprehensive exploration of the complex challenges and risks inherent in mechanized tunneling projects, presenting a robust framework for effective risk management strategies adaptable to diverse environments. Beginning with a thorough introduction that outlines the study's objectives, scope, and limitations, the research delves into a detailed examination of risk factors, project development processes, and existing risk management techniques through an extensive literature review.

Through methodical research design and analysis methodologies, including numerical modeling and risk assessment procedures tailored to mechanized tunneling, the thesis identifies hazards and proposes both quantitative and qualitative risk analysis methods. The development of specific risk management strategies, particularly addressing risks associated with jamming and shallow or deep tunnel conditions, showcases the depth of understanding achieved in this study.

By leveraging advanced analytical tools like axial-symmetric FEM and considering time-dependent ground behavior, the thesis offers valuable insights into mitigating jamming risks and enhancing project safety. Furthermore, the evaluation of numerical simulation results and the proposal of risk mitigation and control strategies underscore the practical applicability of the research findings.

Ultimately, the proactive and integrated approach advocated in this thesis holds significant promise for enhancing the safety, resilience, and sustainability of tunneling projects worldwide. As a valuable resource for stakeholders involved in the planning, design, and execution of mechanized tunneling endeavors, this comprehensive framework paves the way for informed decision-making and successful project outcomes in diverse landscapes and challenging conditions.

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