IMPACTS OF GEOTECHNICAL ASPECTS IN TUNNELING DESIGN AND CONSTRUCTION

by

MOHAMMAD HAADI SADAGHIANI

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They all encouraged me, taught me and loved me unconditionally. I truly dedicate this thesis to my family.

Above all, I am thankful of ALLAH (SVT) for everything I have and achieved in my life.

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ABSTRACT

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Mohammad Haadi Sadaghiani, MS

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Supervising: Professor: Mohammad Najafi

In a tunneling project, different types of methods are conducted to complete a project. Knowing the geotechnical aspects of a tunnel project is unavoidable and crucial in early stage of a project especially before a contract is finalized. This gives the time needed to execute an efficient and more accurate design and helps to prevent cost overruns. Pre-contract time can reduce the bid price and lessen project risks. However, all geotechnical information should be based on standard guidelines such as the American Society of Civil Engineers' (ASCE's) Geotechnical Baseline Report (GBR) to enable provision of the geotechnical data needed in the bid contract for use as a guideline and to prevent future claims or disputes. The main objective of this thesis is to illustrate the importance of geotechnical investigation in the early stage of tunnel project design to measure the impact of geotechnical information on a project from different perspectives. To conduct this research, first, a comprehensive literature search was conducted. Second, a case study was used from a real project to demonstrate what type of geotechnical investigation was conducted for that project before and after the contract was signed. A qualitative analysis was performed to compare the case study project's contract with the GBR standard to determine deficiencies in the contract and project. In conclusion, a general questionnaire was prepared to clarify issues and important factors of the project. This questionnaire was answered by the owner, consulting engineer, and contractor's representatives.

The main technical and geotechnical challenges and risk factors were identified and their effect was analyzed and discussed. Finally, numerical modeling utilizing the finite element method by PLAXIS was conducted to determine how a lack of appropriate geotechnical investigation increases the cost of the project and the risks for owner by increasing the bid price and consequently the total cost of project. Then, cost estimating was performed that showed how the owner could have saved at least 6% in final lining support system and approximately 10% to 20% in the total cost of this tunneling project.

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CHAPTER 1

INTRODUCTION

1.1 Need Statement

Growing population and economy at the current rate of global urbanization causes inherent limitations and issues for transportation, working and living space, traffic, and the environment. One of the main solutions to improve and facilitate living is using underground infrastructure for different purposes. However, underground infrastructure like tunnels and pipelines are more complex and intricate, compared to other sectors (Najafi, 2005). Construction of underground infrastructure, specifically in large-scale tunneling, comes with many risks for all parties involved in the project. Regarding the intrinsic uncertainties, including soil and groundwater conditions, there might be major environmental risks, cost overruns and delays (North American Tunneling et al., 2014).

Tunnels are a feasible solution for crossing a water body or traversing through physical barriers such as mountains, existing roadways, railroads, or facilities; or to satisfy environmental or ecological requirements (Hung et al. 2009, Najafi, 2010). Moreover, tunnels are a permanent solution to minimize potential environmental impacts on society, such as traffic, pedestrian movement, air and noise pollution, or visual intrusion; to protect areas of special cultural or historical value such as the safekeeping of zoned areas, buildings or private properties, or for other sustainability reasons such as to avoid disturbing natural habitats (Hung et al. 2009). Figure 1-1 illustrates the portal for the Glenwood Canyon Hanging Lake and Reverse Curve Tunnels.

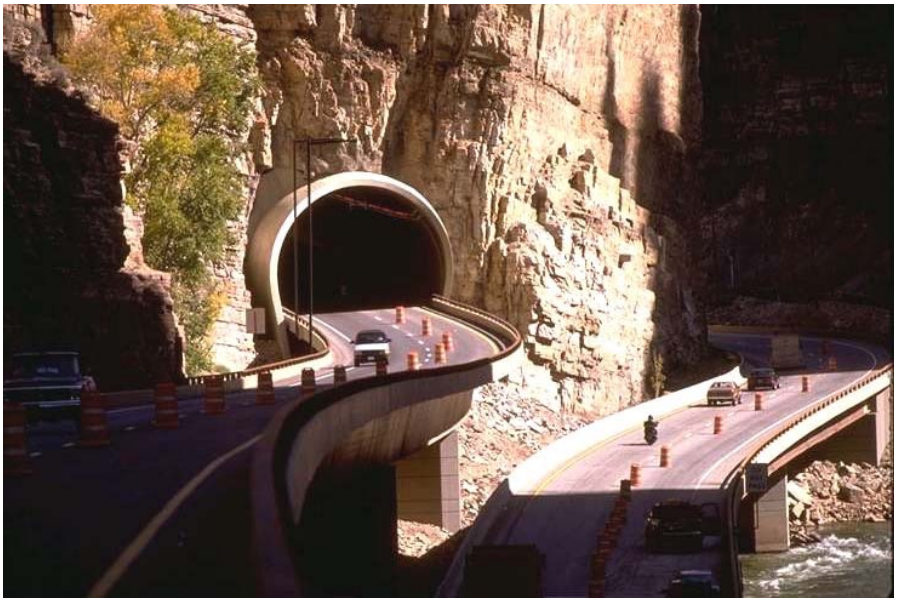

Figure 1-1 Glenwood Canyon Hanging Lake Tunnels
(Hung et al. 2009, p. 1-1)

Construction of tunneling projects can be executed through several phases (Hughes and Murdoch, 2001). Five main phases must be completed to successfully execute each project. These phases include project definition, design, contract, construction, and completion. Each of these steps contain several activities and tasks that must be performed to complete a project successfully (Habibi 2018). To achieve a successful project, considering risks plays a crucial role. According to Smith et al. (2009), "the management of risk is a continuous process and should span all the phases of the project."

The main research needs of this thesis are:

- To analyze and assess geotechnical aspects of a tunnel project based on GBR,
- To demonstrate impacts of geotechnical investigations in tunneling design and back-analysis of construction costs, and
- To assess impacts of geotechnical investigations in risk sharing.

1.2 Research Objectives

The primary objective of this thesis is to identify geotechnical risks for a case study project by interview and GBR-ASCE guidelines. The secondary objective is to measure economic impacts of geotechnical study.

1.3 Research Scope

The scope of this thesis involves the following tasks:

- Assess the impact of the soil modulus of deformability (*Es*) parameter on tunnel design.
- Conduct geotechnical investigation called for in contract
- Design final lining system in tunneling
- Conduct numerical analysis by finite element using the PLAXIS finite element software
- Analysis and discussion of geotechnical investigation of a case study based on ASCE GBR standard

The following is excluded in this thesis:

- Other geotechnical parameters of soil
- Design of other structural sections in tunnel
- Impacts of overburden and soil adhesion in tunneling design and construction

1.4 Methodology

According to the proposed objectives, several tasks were conducted to achieve the goals of this thesis. These steps are demonstrated in Figure 1-2. As stated in the previous section, the focus of this research is on the impacts and importance of geotechnical investigation in tunneling design and construction.

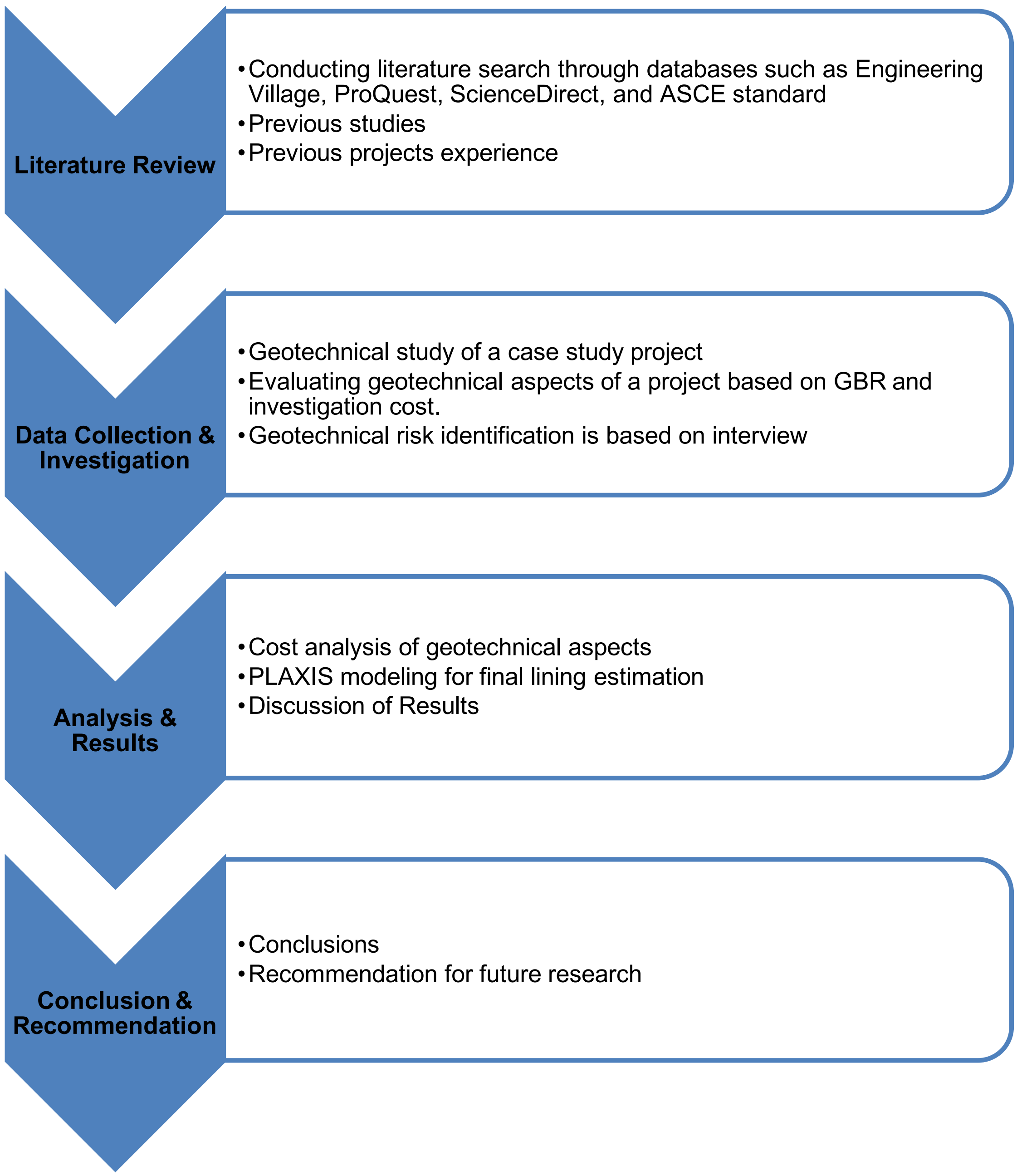

Figure 1-2 Research Methodology

1.5 Expected Outcomes

According to objectives and methodology, several outcomes are expected from this research. They are:

- Comprehensive study on evaluation of important factors and experiments of geotechnical investigation in tunnel project,
- Determining geotechnical aspects in tunneling project,
- Identifying and measuring of geotechnical risk in tunnel project,
- The effect of early geotechnical investigation on the cost savings of project.

1.6 Chapter Summary

This chapter introduced background information about the importance of underground infrastructure, specifically tunneling projects. The main issues described pertained to tunneling project design and construction. Research needs, objectives and scope of work were presented. Finally, the methodology and expected outcomes for this study are provided.

CHAPTER 2

LITERATURE REVIEW

Design and construction of a tunnel requires a multi-disciplinary approach, functional involvement, and assessments. Construction costs and the project lifecycle assessment should be performed and verified. Life expectancies of tunnels are significantly longer than those of other facilities such as building, bridges, or roads (Williams 1997).

A road tunnel can be an effective alternative vehicular transportation system, instead of a surface road or bridge. It can save time and shortens distance. Road tunnels can also make vehicle traffic possible through barriers and obstacles that would otherwise be impossible such as mountains and rivers (Leca et al. 2000). Tunnels alleviate surface congestion, reduce air pollution and noise, and minimize surface disturbance (English 2015). When planning the design and construction of a tunneling project, the following issues should be considered (Hung et al. 2009):

- Subsurface geological and geo-hydraulic conditions,
- Constructability,
- Seismicity,
- Long-term environmental impact,
- Life cycle of tunnel,
- Potential air right developments,
- Land use restrictions,
- Economic benefits and life cycle cost,
- Maintenance and operation,
- Security,
- Sustainability.

2.1 Geotechnical Aspects in Tunnel Projects

Geotechnical aspects are crucial for appropriate tunnel design. Selection of alignment, longitudinal profile, cross section, and construction methods is influenced by the geological and geotechnical conditions as well as site limitation (Council 1984). Knowledge of the expected geological conditions is vital. The type of ground conditions along the alignment has an important role in the selection of the tunnel type and its method of construction (Hoek 1982).

Geotechnical features such as soil or rock properties, ground water condition, and ground coverage (e.g., overburden) above the tunnel must be considered. Manmade problems such as the presence of contaminants along the tunnel route and presence of underground utilities must be dealt with. Obstructions such as boulders or buried objects, and the presence of sensitive surface facilities when evaluating tunnel alignment must also be evaluated (Leca et al. 2000). Based on the results of the geotechnical investigation, tunnel alignment is sometimes changed to minimize construction cost or to reduce risks (Hoek 1982). The tunnel profile can also be adjusted to improve constructability or accommodate construction technologies as long as the road geometrical requirements are satisfied (Hung et al. 2009).

2.1.1 Geotechnical Investigation in Tunnel Design and Construction

Design and construction of a tunnel project requires different types of investigative techniques to get a broad insight into the relevant topographic, geologic, subsurface, geo-hydrological, and structure data needed for a successful plan (Council 1984). The extent of the investigation should be consistent with the project scope (i.e., location, size, and budget), the project objectives (risk tolerance, long-term performance), and the project constraints (geometry, constructability, third-party impacts, aesthetics, and environmental impact) (North American Tunneling 2014).

The involved parties should have a common understanding of the geotechnical basis for design, which is very important, and they should be aware of the unavoidable risk of not being able to completely define existing subsurface conditions or to fully predict ground behavior during construction (Sham et al. 2011). Generally, an investigation program for the planning and design of a tunnel project may include the following components (Viggiani 2012):

- Existing Information, Collection, and Study,
- Surveys and Site Reconnaissance,
- Geologic Mapping,

- Subsurface Investigations,
- Environmental Studies,
- Seismicity,
- Geospatial Data Management.

2.1.2 Geotechnical Investigation Steps

The primary aim of any geotechnical investigation should be to obtain the maximum amount of information on rock characteristics, structural systems and groundwater conditions (Brierley 1998). Among the higher cost of a complete geotechnical investigation for different types of tunnel projects, which is mostly around 3% to 5% of construction cost, it is more effective to implement geotechnical investigations in early phases to focus the effort in the areas and depths that are important (Hung et al. 2009).

Figure 2-1 Water Boring Investigation in Miami Tunnel
(Hung et al. 2009, p. 3-2)

Phasing in geotechnical investigations provides an economical and logical approach to adoption of these anticipated changes to the project. Typical stages of a tunnel project from concept level to completion (Council 1984) are as follow:

- Planning,
- Feasibility Study,
- Corridor and Alignment Alternative Study,
- Environmental Impact Studies (EIS) and Conceptual Design,
- Preliminary Design,
- Final Design, and
- Construction.

Geotechnical investigations provide an economical and logical approach for adding anticipated changes to the project (Hoek 1982). Figure 2-2 demonstrates the flow process of the phases of the geotechnical investigations. Figure 2-2 shows the importance of geotechnical investigation for design verification, which can influence project completion during project lifecycle.

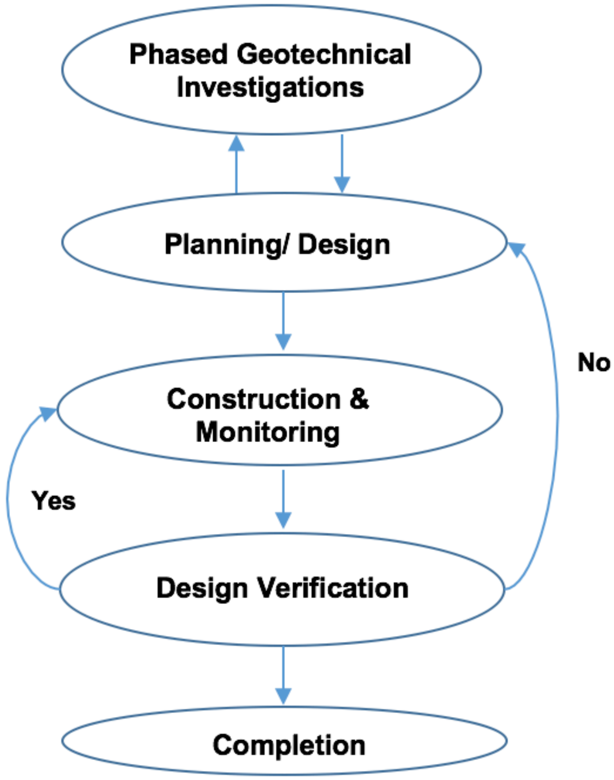

Figure 2-2 Phased Geotechnical Investigations with Project Development Process
(Adopted from Hung et al. 2009)

2.1.3 Geotechnical Investigation Study

2.1.3.1 Review and Collecting of Existing Data

The first step in understanding the site conditions and limitation of costs is to collect and review existing information. Factors that may influence the design and construction of the tunnel can be recognized by this available information (Page et al. 2005).

2.1.3.2 Topographic Data

Topographic data can often, by interpretation, show geologic structures when overlapped with published geological maps. The site history may reveal earthwork, erosion and scouring, and often include past construction aerial photographs taken on different dates (Williams 1997).

2.1.4 Site Reconnaissance and Surveys

2.1.4.1 Preliminary Surveys and Site Reconnaissance

A preliminary design to expand existing topographical data and a preliminary survey for concept development can be obtained by getting data from field surveys and an initial site reconnaissance (Mayne et al. 2002). Geologic, hydrologic and seismic effects can be determined from on-site reconnaissance, which should cover the project's immediate area, as well as the larger surrounding regional area (Mayne et al. 2002).

2.1.4.2 Topographic Surveys

Detailed topographic maps, plans and profiles must be developed to establish primary control for final design and construction based on a high order horizontal and vertical control field survey. Accuracy of topographic mapping is essential to support surface geology mapping and the layout of exploratory borings, whether existing or performed for the project (Council 1984). The principal survey techniques are as follow (Hung et al. 2009):

- Conventional Survey,
- Global Positioning System (GPS),
- Electronic Distance Measuring (EDM) with Total Stations,
- Remote Sensing, and
- Laser Scanning.

Figure 2-3 3D Laser Scanning Tunnel Survey Results in Actual Scanned Points
(Hung et al. 2009, p. 3-7)

2.1.4.3 Preconstruction Survey

A preconstruction survey can verify all the related facts of conditions and clarify features and locations for controlling and monitoring. This survey recognizes the potential impacts on structures which helps engineer to initiate protective strategies and ensure all potential disruptive force-sensitive data is made available at all times. This data can pertain to structures located in a specific sensitive zone with a different type of force that causes vertical and lateral movement due to soil movement. This type of movement can also be caused by tunnel excavation and construction, as noted in the preconstruction survey (Brierley 1998). Naturally, this type of area requires extra precautions.

2.1.5 Geological and Geotechnical Investigation

Additional geological and geotechnical investigation is often necessary to get the appropriate information required to reach a more accurate and practical design for the final construction of tunnel projects. This information follows these aims (Bieniawski 1989):

- Exploration ahead of the advancing face to probe zones for potential high-water inflow, poor ground, limestone caves, buried valleys, or dips in the weathering profile,

- Rock mass classification to verify initial ground support,
- Finalizing tunneling lining design regrading verified assumed conditions, and
- Documenting for future use in operations, inspections, and maintenance work by interpreting and extrapolating all data from all sources, with special attention to data from geologists and geotechnical engineers so everyone can have a better understanding of the rock conditions. This is critical when determining a good method for tunneling excavation and selecting the best method for construction (Bieniawski 1989).

2.1.5.1 Soil Identification and Classification

Field classification of soil for most tunnel projects is similar to other geotechnical applications except that special attention must be performed to accurately document and define soil grade and grain size characteristics and stratification features. These properties may have a greater effect on the ground and ground water behavior during tunneling construction than other types of construction projects. Important items for tunnel projects follow (Karlsson and Hansbo 1981):

- Ground water levels, ground permeability, evidence of artesian conditions,
- Consistency and strength of cohesive soils,
- Composition, graduation and density of cohesionless soils,
- Presence of lenses and layers of higher permeability soils,
- Presence of gravel, cobbles and boulders, and potential for nested boulders,
- Presence of cemented soils, and
- Presence of contaminated soil or groundwater.

All of these factors will effectively affect ground behavior and groundwater inflow during construction, and the selection of the tunneling equipment and methods (Karlsson and Hansbo 1981).

2.1.5.2 Rock Identification and Classification

In ground condition and behavior during a tunneling project, rock mass features have more impact on construction than other characteristics such as intact rock properties. Consequently, engineers should focus on the rock mass characteristics and rock mass classification as they pertain to intact properties and origin of conditions for tunneling applications and methods of excavation

(Barton 1988). The major practical engineering rock mass classification systems are shown in Table 2-1.

Table 2-1 Major Rock Classification Systems Currently in Use (Barton 1988)

Name of Classification	Originator and Date	Country of Origin	Application
Rock Loads	Terzaghi (1946)	United States	Tunnel with Steel Supports
Stand-up Time	Lauffer (1958)	Austria	Tunneling
Rock Quality Designation	Deere (1968)	United States	Core logging, Tunneling
RSR[1] Concept	Wickham et al. (1972)	United States	Tunnel with Steel Supports
Geomechanics (RMR[2])	Bieniawski (1979)	S. Africa	Rock Mass, Tunnels, Mines
Q-System	Barton et al. (1974)	Norway	Tunnels, Large Chambers

[1]Rock Structure Rating, [2]Rock Mass Rating

Regular characteristics, which consist in describing typical rock lithology follow (Bieniawski 1989).

- General rock type,
- Color,
- Grain size and shape,
- Texture (stratification, foliation, etc.),
- Hardness,
- Strength,
- Mineral Composition,
- Roughness and Abrasiveness, and
- Weathering and alteration.

Rock Quality Designation (RQD) is one of the index properties that is obtained from sample rock core, which helps engineers understand rock mass quality hardiness and competency (Deere 1988). Table 2-2 shows the quality of rock classification based on RQD percentage.

Table 2-2 Description of Rock Quality Based on RQD (Deere, 1988)

RQD %	Description of Rock Quality
0–25	Very Poor
25–50	Poor
50–75	Fair
75–90	Good
90–100	Excellent

2.1.6 Subsurface Investigation

Fundamentally, subsurface investigation is the most important part of geotechnical investigations and is needed to achieve information about ground conditions at depth, which includes geological, geotechnical, hydrological, and groundwater conditions that have a very important impact on the planning, design, construction and even operation of tunnel projects. The use of this information is the practical and principal means for determining the points that follow (Mayne et al. 2002).

- Defining the subsurface profile of ground (soil and rock type),
- Determining soil and rock characteristic and features,
- Identifying geological aspects such as fault zone and other hazards,
- Determining hydrogeological conditions (ground water levels and pressure, aquifers, etc.),
- Identifying potential construction risks (boulders, etc.),
- Understanding the subsurface structure by boring to get samples for visual classification and laboratory testing,
- In situ testing to obtain valuable index and engineering properties, i.e., testing material in place to avoid the disturbance; in addition, in situ tests can also aid in defining stratigraphy,
- Geophysical tests quickly and economically achieve subsurface information over a large area to identify suitable location for boring, and
- Laboratory testing provides a wide variety of engineering and index properties from representative soil and rock samples retrieved from borings.

2.1.6.1 Test Borings and Sampling

Vertical and/or Inclined Test Borings

Soil and rock sampling are key elements of any subsurface investigation for underground projects; one way to get the samples is by drilling vertical and/or slightly inclined test borings, as illustrated in Figure 2-4.

Figure 2-4 Vertical Test Boring/Rock Coring
(Devin, 2016)

Table 2-3 presents general guidelines from AASHTO (T307-99, 2003) for determining the spacing of boreholes for tunnel projects:

Table 2-3 Guidelines for Vertical/Inclined Borehole Spacing (AASHTO T307-99, 2003)

Ground Conditions	Typical Boreholes Spacing (m)
Cut and Cover Tunnels	30 to 90
Rock Tunneling	
Adverse Conditions	15 to 60
Favorable Conditions	150 to 300
Soft Ground Tunneling	
Adverse Conditions	15 to 30
Favorable Conditions	90 to 150
Mixed Faced Tunneling	
Adverse Conditions	7 to 15
Favorable Conditions	15 to 23

Directional and Horizontal Coring/Boring

This type of sampling provides a continuous record of ground texture and structure, which is directly related to tunnel alignment. Horizontal coring/boring is usually conducted from inside the tunnel face (AASHTO T307-99, 2003).

Sampling – Overburden Soil

Standard split spoon (disturbed) soil samples (ASTM D1586 2011) are typically obtained at intervals not greater than five feet and at are noted when a change occurs in the type of strata. Continuous sampling from one diameter above the tunnel crown to one diameter below the tunnel invert is advised to better define the stratification and materials within this zone if within soil or intermediate geomaterial.

Figure 2-5 Rotosonic Sampling for a CSO Tunnel at Portland, Oregon
(Hung et al. 2009, p. 3-18)

Sampling – Rock Core

The following information is recommended to be noted for information on boring and core run on the rock coring logs (Hung et al 2009):

- Depth of core run,
- Core recovery,
- Rock Quality Designation (RQD),
- Rock characteristic such as type, color texture, degree of weathering, and hardness,
- Features of joint spacing, orientation, roughness and alteration,
- Nature of Joint infilling materials.

Figure 2-6 illustrates samples of rock core.

Figure 2-6 Rock Core Samples in Core Box (ALS Global 2017)

Test Pits

To investigate in shallow conditions, location and depth of existing utilities and other underground specification that may interfere or be impacted by the construction of portals, shafts and cut and cover tunnels, test pits have been identified as a good solution (Mayne et al. 2002).

2.1.6.2 Field Testing Techniques (Pre-Construction)

Field-testing for subsurface investigations includes two general categories of tests (Mayne et al. 2002):

a) In-situ tests
b) Geophysical testing

In-situ Testing

In situ tests are used to directly obtain field measurements of useful soil and rock engineering properties (ASTM D1586 2011). Figure 2-7 illustrates the field plate load test.

Figure 2-7 In-situ Plate Load Test (Dunelm 2017)

Geophysical Testing

Geophysical tests are indirect methods used to discover the changes in certain physical properties as an aid in developing underground information. These changes include elasticity, density, electrical resistivity, or a combination of such changes (Brierley 1998)

2.1.6.3 Laboratory Testing

For obtaining accurate information for tunneling design and modeling purposes, detailed laboratory testing is essential based on the classifications determined by Head and Epps (1980) which is divided in two sections:

Soil Testing: To obtain accurate information on classification, characteristics, stiffness, strength, etc., detailed soil laboratory testing is essential (Head and Epps 1980).

Rock Testing: Standard rock testing analyzes physical features of the rocks including density, permeability and mineralogy (thin-section analysis) (Head and Epps 1980).

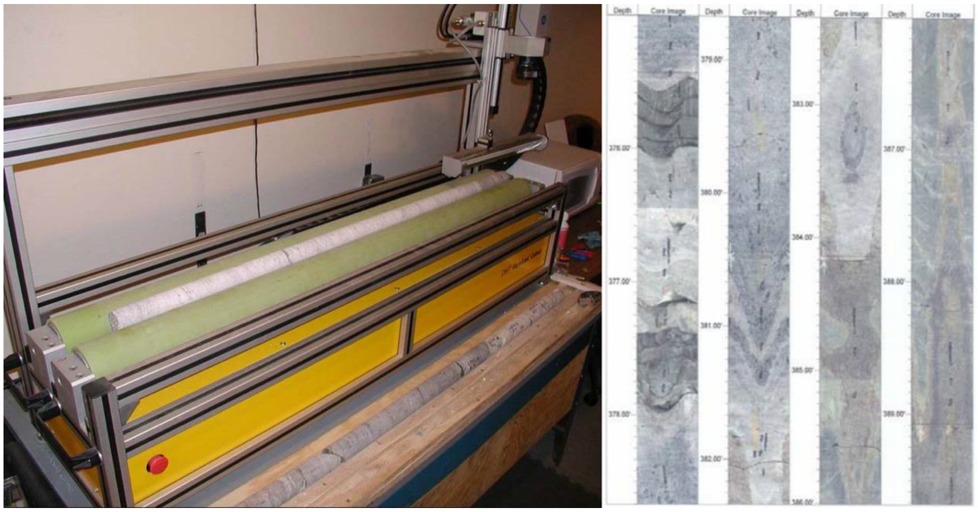

Figure 2-8 Rock Core Scanning Equipment and Results (Hung et al. 2009, p. 3-30)

2.1.7 Ground Water Investigation

A major challenge for all types of projects (specifically for tunneling and underground infrastructure) are ground water condition (Legchenko et al. 2003). Ground water in tunneling may not only present a considerable factor for loading on the tunneling design, but ground water also affects the ground characterization, behavior and stability of tunnels especially soft ground tunnels. Ground water investigations include the following actions (Mandel 2012):

- Measurement of groundwater levels in boreholes,
- Assessment of soil moisture changes in the boreholes,
- Groundwater sampling for environmental testing,
- Installation of groundwater observation wells and piezometers,
- Borehole permeability tests (packer tests, falling and constant head tests, rising),
- Geophysical testing, and
- Pumping tests

2.2 Geotechnical Baseline

2.2.1 Introduction and Development of GBR in Tunneling Project

Underground conditions have always presented significant risks of unknown occurrences and factors, which are difficult for engineers and contractors to anticipate and predict. Most of the time, contractors face situations that are more adverse than expected. These problems have led to significant increases in projected costs, delayed construction schedules, and disputes between the owner(s), contractors, and engineers (Hashash et al., 2014).

The Geotechnical Baseline Report (GBR) is a contractual document and specific report that sets baselines and principles during construction to simplify risk factors and make them more manageable as they occur in different projects (Hashash et al. 2014). Table 2-4 shows the process of the evolving GBR in the construction industry.

Table 2-4 Evolution of Geotechnical Baseline Report (Dwyre et al. 2010)

Year	Document	Geotechnical Reporting Concept of Growth
1974	Better Contracting for Underground Construction	• Basic principles of subsurface risk allocation
1989	Avoiding and Resolving Disputes in Underground Construction	• Geotechnical Design Summary Report (GDSR)
1991	Avoiding and Resolving Disputes in Construction	• Expansion of GDSR concepts
1997	Geotechnical Baseline Reports (GBR) for Underground Construction	• Geotechnical Data Report (GDR), Geotechnical Interpretive Report (GIR), with GBR defined and their contents outlined. • GBR replaces GDSR
2007	Geotechnical Baseline Reports for Construction	• GDR and GBR part of contract documents • GIR no longer recommended • GBR broadens applications beyond underground construction • Application to Design-Build

The Geotechnical Baseline Report (GBR) may be the most important improvement in contracting practices in the construction industry, especially in tunneling projects. This report as a construction contract has clarified and established contractually binding specifications pertaining to related physical and behavioral conditions in different situations for the parties who will be responsible (Dwyre et al. 2010).

The GBR gives the parties a chance to allocate risks using regular and legal options, referred to as risk sharing. The brief objectives of these kinds of risk sharing approaches in tunneling follow (Salam 1995):

- Lowering the contractors' uncertainty based on the financial risks of tunneling projects to obtain the lowest bid prices,
- Promoting greater cooperation between the contractor and the owner,
- Resolving disputes between the contractor and the owner much faster and more fairly when ground conditions encountered during construction differ substantially from those reflected in the contract documents at the time of bidding, and
- Working to achieve the lowest final cost for the project.

After years of experience and geotechnical knowledge development, which helped to establish the contracting practices in different types of project, especially in tunneling projects, Essex (2014) defined five key elements) that have often been implemented over the years. They are:

- Geotechnical Data Report,
- Geotechnical Interpretive (Baseline) Report,
- Differing Site Conditions Clause,
- Escrow Bid Documents, and
- Disputes Resolution Board.

The most important of the five is GBR. GBR and GDR are discussed in the following sections.

2.2.2 Geotechnical Data Report

A Geotechnical Data Report (GDR) is a geotechnical document that is integrated into the construction contract. A GDR should have real and factual information that has been gathered during the exploration and design phases of the project (Essex, 2014). Surveying and experimental methods and/or procedures technically influence the reliability of underground information. Consequently, the

GDR should have these data based on the Geotechnical Baseline Reports for Construction, more commonly known as the American Society of Civil Engineers' GBR. (ASCE 2007). A GDR mostly provides results from the field and laboratory tests and procedures employed. A GDR will contain:

- Descriptions of the geologic conditions,
- Descriptions of the site exploration program(s),
- Logs of all borings, trenches, and other site investigations,
- Descriptions/discussions of all field and laboratory test programs,
- Results of all field and laboratory testing.

2.2.3 Geotechnical Baseline Report

2.2.3.1 GBR Definition and Purposes

While the Geotechnical Data Report provides a contractual set of information, the Geotechnical Baseline Report (GBR) provides a contractual set of explanations based on data and other considerations available to the engineers and the design team (Essex 2014). The GBR implements a contractual understanding of the geotechnical conditions of the project, which establishes baselines to consider and envisage during construction (Essex 2014).

The GBR is very useful in several ways. First, it provides bidders an accurate and clear format of ground conditions with all details and specifications. Secondly, all bidders are forewarned that the GBR should be used to develop their bids and to obtain a real and logical understanding of baseline conditions and behaviors in their evaluation for pricing (ASCE 2007). The primary purposes of the GBR are:

- To instate a contractual document with baseline conditions that determine the specific underground conditions, which should be considered by contractors in preparing and evaluating their bids,
- To establish a contractual procedure for modification of project cost when subsurface conditions met during construction are poorer than the baseline conditions defined in the contract documents (an attempt to prevent probable disputes and claims between parties).

The GBR also reflects the result of geotechnical investigations and design studies. However, it is not intended to anticipate the real geological and geotechnical conditions at a project location or have an accurate prediction of the ground condition and behavior during construction. Even, it establishes the principles for ascertaining the financial risk between the owner and the contractor. In addition, the ASCE GBR (ASCE 2007) lists the secondary aims of the GBR, which is listed below:

- Serves as basis of design extracted from the presented geotechnical and geological considerations,
- Elucidates vital considerations that need to be addressed during bid preparation and construction,
- Elevates understanding of contractor in key factors regarding project issues and limitations, and provides the contract plans and specifications,
- Evaluates the requirements for tunneling excavation which makes obtaining support easier for contractor based on GBR,
- Makes it easier for a supervisor such as the construction manager to manipulate the contract and control contractor performance

Essex (2014) indicated: “Baseline statements should be considered as a contractual assumption, not necessarily geotechnical fact”, which demonstrates the importance of GBR as based on reports prepared by different members of a design team. Those interpretive reports can cover a vast range of design issues for internal consideration by the whole GBR team. This type of input gives the GBR a certain flexibility.

GBR should represent a reasonable extension of available information, which can summarize potential conditions outside the GBR to determine risk factors, which include both the owner’s and contractor’s conceptual risk sharing as shown in Figure 2-9. This Figure illustrates that if the owner has a geotechnical investigation conducted early in the pre-negotiation stage of project, it can reduce risk when shared with contractors; otherwise, the owner risk will increase (Essex 2014).

Figure 2-9 Conceptual Baseline Report Risk Sharing
(Adopted from Essex 2014)

Furthermore, the owner should be involved with the setting of the baselines and understanding the consequences of where the baselines are set.

2.2.3.2 GBR Features and Practices

A geotechnical baseline should clearly distribute and establish the boundaries of those conditions that can lead to better risk allocations and determine how they are measured (Hashash et al. 2014). The GBR may not show any obligation by the designer of the project. Thus, geotechnical engineers tend to distribute and develop conservative baselines to gain a small margin of potential responsibility for all parties (Dwyre et al. 2010).

2.3 Geotechnical Risk in Tunneling Project

2.3.1 Risk Sharing in Tunneling Project

It has long been recognized by knowledgeable engineers in the tunneling industry that underground contracting practices must be implemented with enough flexibility to address unexpected obstacles (risks) and still have enough time to meet deadlines under predefined cost and safety constraints. The ultimate goal is the long-term durability of the final system. This requires a contract system, which can follow basic, common sense steps to accomplish an efficient, smooth-running operation within a reasonable budget and timeline. Salter (1992) outlined the basic steps over 20 years ago, which are 1) define the objective of the project, 2) design and plan the project, 3) implement and construct the project.

The ultimate realization of such projects requires complete cooperation, assistance and understanding among the three main partners who help negotiate the contract: the owner, the contractor, and the consulting engineer. The ideal contract is one, which defines the obligations and commitment of each party clearly and is set up in such a manner that the project is brought to reality with all goals achieved in an economical manner. This is internationally known as risk sharing involving all three of the main partners (Salam, 1995).

Contracts of tunneling and underground projects must include special consideration. In these projects, the contractor should face with variety of uncertainty, which is resulting in significant risks specifically in urban area. Major risks are as follow:

- Potential damage to the properties of third parties or public,
- Risks involving equipment and safety of workforce,
- Risk of failure to meet deadline—only partially completing work of the employer.

The characteristics of tunneling are its linear form and the continuous revelation of site conditions not entirely known at the start of construction. Unexpected obstacles, including those resulting from unforeseen site conditions and the construction medium, have a greater impact on the progression of work because interruptions in the continuous construction process can present serious physical and financial risks to both the contractor and the employer (Eskesen et al. 2004).

Because of the wide variety of contracts used in major civil engineering projects, general guidelines are difficult to formulate. However, the overall objectives are the same. Failure to minimize cost and schedule overruns lead to disputes that are common in the workplace and need to be addressed by better contracts (Eskesen et al. 2004). Contracts must comply with state and federal laws and meet job expectations with some room left for failure due to natural causes and cost overruns, with a recommended procedure for resolving disputes involving key issues

2.3.2 Geotechnical Risk Factors in Tunnel Project

A main cause for cost and schedule overruns on tunneling and underground projects is unpredicted geological conditions and related geotechnical issues (Sham et al. 2011). Contracts have many different types of clauses to address these issues; the best solution is to have an accurate and valid definition of geotechnical conditions in the early stage of the project. This can give a better prediction of the site condition, which enables adequate preparation to deal with the problem and thereby minimize geotechnical risks in the tunnel project (Hoek 1998).

Contractual agreements have improved their risk management clauses regarding tunneling and underground accidents due to natural causes. However, even though these changes have had effective influences regarding budget planning, concerns remain, specifically the geotechnical risks of tunneling projects in urban area. Understanding geotechnical and geological conditions in urban tunneling construction is a more complicated issue because of underground utilities such as pipelines, optical fibers, and other utilities, which must be, protected (Najafi, 2005).

Pre-knowledge of both the geotechnical risks and geological conditions is essential to a successful project. It can also increase costs and schedule overruns especially for tunneling and underground projects.

The World Bank annual report (World Bank 1996) states:

"Changes in project scope during implementation can have a significant impact on the project cost and schedules. Such changes can arise, for example, from the inability of design-stage investigation to eliminate risks from unknown geological conditions for construction of underground works, particularly for many hydropower projects. In addition, for first-of-a-kind projects in developing countries, project estimators do not have a record of accomplishment of similar projects as a basis for carefully analyzing major construction risks and deriving reliable contingencies for them. Instead, they often rely on unreliable rules of thumb for such contingencies."

The World Bank annual report (World Bank 1996) pointed out that geotechnical conditions are suffering from lack of suitable and reliable data and information for evaluating geotechnical risks. Basically, adequacy of the information obtained only from the site investigation program (Council 1984). ASCE (Essex 2007) recommends the following measures for decreasing geotechnical risks in contractual agreement:

- Provide enough funding to detect subsurface conditions,
- Work with qualified and experienced engineering consultants to investigate, evaluate potential risks in different stages,
- Allot adequate time and budget resources to prepare a clear geotechnical baseline report that is consistent with other design documents,

- Develop unit price payment provision that can be adjusted to the conditions encountered,
- Review and discuss the baseline with the bidders before the bids are submitted,
- Maintain a suitable reserve fund, depending upon the perceived risks of the project.

Geotechnical risks, in the form of unpredictable geological conditions, are a serious factor in cost and schedule controlling on tunneling projects. The amounts of budgets, involved in claims arising from these geotechnical problems is huge and needs to be considered very seriously by financing agencies and engineering firms. Hoek (1998) explained stages in a tunnel project development with the following table (Table 2-5).

Table 2-5 Geotechnical Factor in Each Stage in Tunnel Project (Hoek 1998)

Stage in Project	Information Required a design method used	Source of information
Feasibility	• Topography, geology groundwater conditions and seismic hazard estimates in project area. • Rock mass classification and estimates of rock mass characteristic and in situ stress conditions, particularly along tunnel routes. • Estimates of tunnel support from rock mass classifications	• Regional topographic, geological and seismic hazard maps, geological information from adjacent projects, possibly limited site investigations to confirm critical geological or groundwater conditions. • The use of geophysics may provide useful information.
Basic Design	• Confirmation and refinement of estimates made during feasibility stage. • Numerical and limit equilibrium analyses of excavation and slope stability. • The quality of information available may not permit 'precise' calculations and sensitivity studies may be required to predict the range of rock mass behavior.	• Topographic survey, surface geological mapping and diamond drilling programs. • Where funds are available, exploration trenches or tunnels can yield very high-quality information. In situ stress measurements using hydro-fracture techniques. • Laboratory tests of rock and soil properties, particularly of weaker units.
Detailed Design and Awarding of Contract	• As for basic design, but with more refined analysis, as better quality information becomes available. • Particular care is required in the preparation of specifications and contracts to minimize the risk of creating problems due to inappropriate wording.	• Exploratory excavations in which detailed geological studies and in situ tests can be carried out, if required. • Pilot tunnels for particularly difficult short tunnels should be considered.

CHAPTER 3

GEOTECHNICAL INVESTIGATION – HAKIM TUNNEL CASE STUDY

3.1 Hakim Tunnel and its Geotechnical Aspects

3.1.1 Description of The Project

To preserve the environment and save *Chitgar Forest Park,* a tunnel was constructed under this park in the form of twin tunnels running in an east-west direction. The length of each tunnel is about one kilometer. They were constructed in stages from both east and west portals, using the New Austrian Tunneling Method (NATM). Figure 3-1 shows the satellite image of the project area.

3.1.1.1 Summary of Geology of the Site

The alluvial deposits of the project location are divided into four formations or series A, B, C, and D (Rieben 1966). The geological characteristics of the existing sedimentary units are as follows:

Alluvial Formation A (Thousand Valley Formation): The name of this formation is due to the morphology of the outcrops of the formation, which is seen due to surface erosion of the groove. Alluvial deposits in Formation *A* are mainly sand with sandstone, silt and clay lenses. The clastic rocks of this formation are almost entirely composed of volcanic deposits and volcanic rocks associated with the Eocene era, which are derived from the northern highlands of the *Alborz Mountain* ranges.

Figure 3-1 Hakim Tunnel Position on a Satellite Image (Google Map)

<u>Alluvial Formation B:</u> This formation is divided into two northern (B_n) and southern facies (B_s). Formation *B* is located on sediments of formation *A* and forms the topographic conic of northern Tehran. The thickness of formation *B* is estimated at about 60 meters. Formation *B* is a blend of sand, rig and clastic stones that is as thick as a cobblestone with a matrix as thick as sand. Therefore, formation *B* is a heterogeneous unit with poor alignment. The diameter of some boulders in formation *B* reaches 4.5 meters. This formation is mostly east of Tehran.

<u>Alluvial Formation C (Tehran Alluvial Formation):</u> Formation *C* consists of young coniferous and alluvial deposits. The sediments of this formation consist of homogeneous alluvial deposits, consisting of gravel and cobblestone sand and gravel, with sand and sandy silt. Coating in *C* formation is better than layering in formation *B*, but less developed than *A* formation. The maximum thickness of this formation is estimated at about 60 m.

<u>Alluvial Formation D (Recent Undertakings):</u> Formation *D* is the youngest stratigraphic unit in the Tehran region, which is in the form of sedimentary and riverine alluvial deposits in the region. Alluvial deposits of this formation consist of sediments that are the size of sand and a ridge with weak, non-intrusive consolidation, which has sand and aggregates. The color of this unit is gray to dark gray and is similar to a *C* formation, with alluvial and river origin. Figure 3-2 shows an image of the dominant sediments of formation *C* and *A* on the Hakim tunnel route.

Figure 3-2 Sediments of Formation *C* (Bottom) and Formation *A* (Above)

3.1.2 Geotechnical Study of the Hakim Tunnel Project

The Hakim Tunnel project was built using a “Design-Build” contract. Geotechnical studies of this project were carried out in two phases for the tunnels. Tehran municipality (the owner) conducted the first phase before the start of the project. Their data were included in the bid and contract documents. Contractor conducted the second phase on the tunnel site after the contract was awarded.

There were also relatively complete geotechnical studies for two projects adjacent to the tunnels. The results of these two studies were not included in the bid documents but were unofficially were available to the bidders. These projects were Chitgar Lake Project and Township Project.

3.1.2.1 Geotechnical studies on the extension of Hakim highway

These studies were carried out by the Center for Geotechnical Studies and Materials Resistance of the Municipality of Tehran as a Phase 1 study. In this operation, five boreholes were drilled at depths of 27 to 40 meters along the tunnel route. Field experiments and laboratory tests were carried out. It should be noted that no analytical report has been provided for these studies. The layout of these specimens on the tunnel route is shown in Figure 3-3.

3.1.2.2 Additional Geotechnical Studies (Phase 2) Hakim Tunnel Project

In these studies, a 30-m machine borehole and six 15-to 30-meter hand drill test pits were drilled in the tunnel route and were used to perform field and laboratory experiments. The planning of these boreholes, test pits, and field and laboratory tests were based on the results of a Phase 1 study and all these types of experiments are explained in Section 2.1.6. Figure 3-3 shows the location of these boreholes and test pits. Table 3-1 lists the coordinates of the boreholes and test pits.

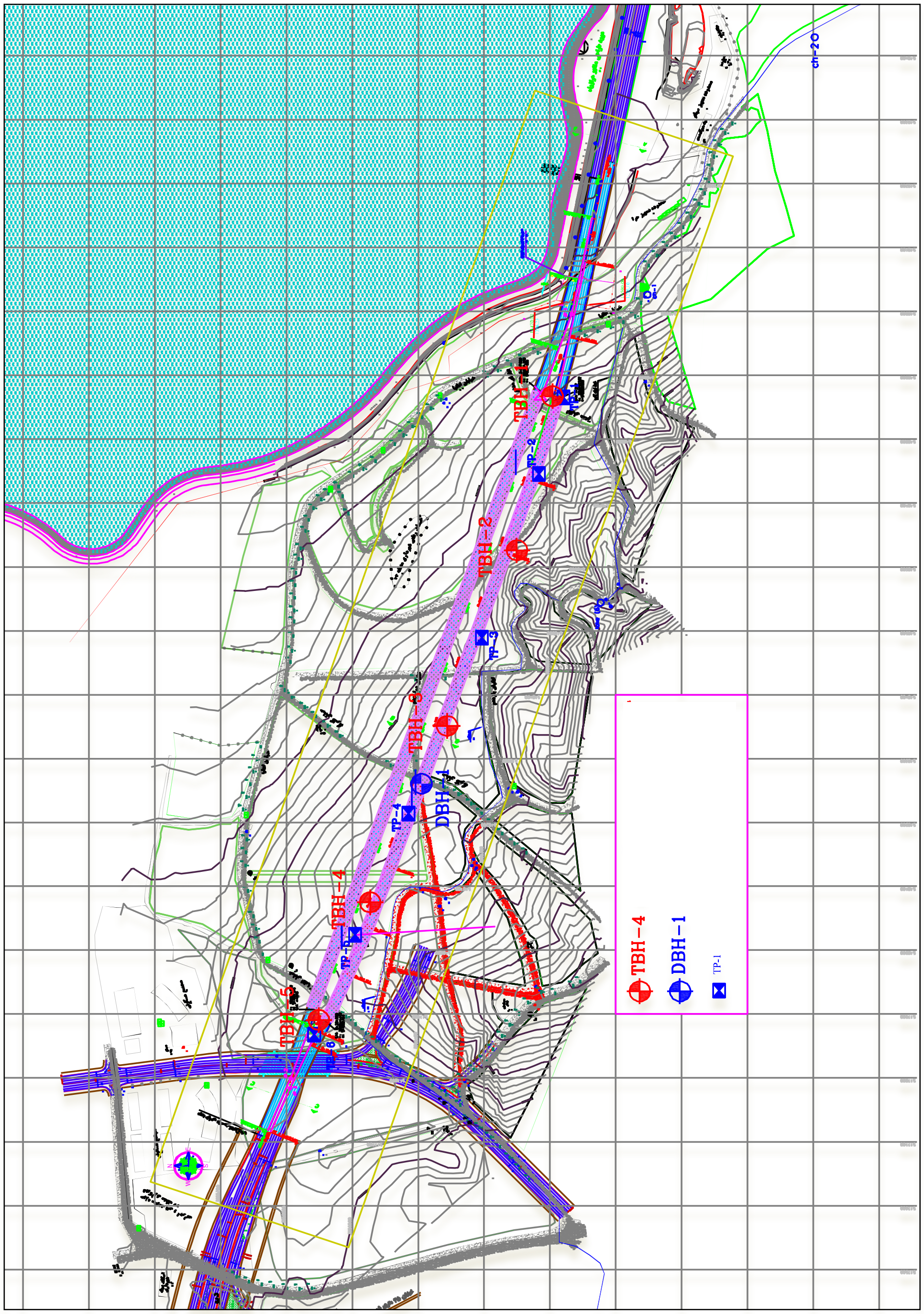

Figure 3-3 Boreholes and Test Pit Drilled along the Tunnel (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

Table 3-1 Coordinates of Machine Drill Boreholes and Test Pit Wells in Phase 1 and Complementary Geotechnical Studies (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

Borehole / well	Depth (m)	X	Y	Z
TBH-1	27.0	518867.6	3955196.1	1271.6
TBH-2	40.0	518626.9	3955250.0	1279.2
TBH-3	35.0	518351.6	3955356.0	1275.9
TBH-4	39.0	518075.5	3955473.4	1281.1
TBH-5	30.0	517891.4	3955551.6	1277.7
DBH1	30.0	518260.2	3955397.0	1279.0
TP1	15.0	518866.4	3955181.2	1271.0
TP2	30.0	518746.0	3955216.0	1273.5
TP3	30.0	518489.2	3955302.9	1273.5
TP4	30.0	518213.5	3955414.7	1279.5
TP5	30.0	518024.2	3955495.2	1279.0
TP6	15.0	517868.0	3955558.1	1279.0

3.1.2.3 Geotechnical studies of Chitgar Lake Project

The Lake Construction Project was located north of the tunnels. There were three machine boreholes at the dam site and 74 hand-drilled test pits in the lake and at the dam axis. Figure 3-4 shows the layout map of wells and boreholes in this project.

3.1.2.4 Geotechnical Studies of Township

The Township is located northwest of the tunnels. For the geotechnical studies of this Township, 48 continuous boreholes with depths of 25-to-100 *m* and 16 test pits of 5-to-18 *m* were drilled. The distance between the town and the western portal of the Hakim Tunnel is about 600 m. In Figure 3-5, the location of the Township is shown. Since ground conditions could be different from point to point with different specifications, geotechnical exploration was done for whole area near the tunnel project location.

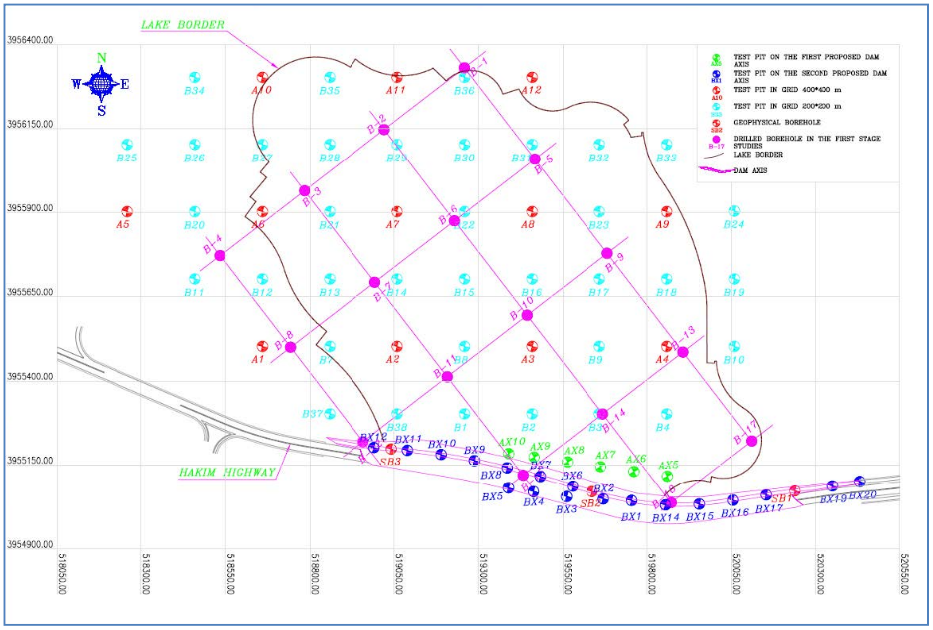

Figure 3-4 Boreholes and Wells Drilled on the Dam and Chitgar Lake (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

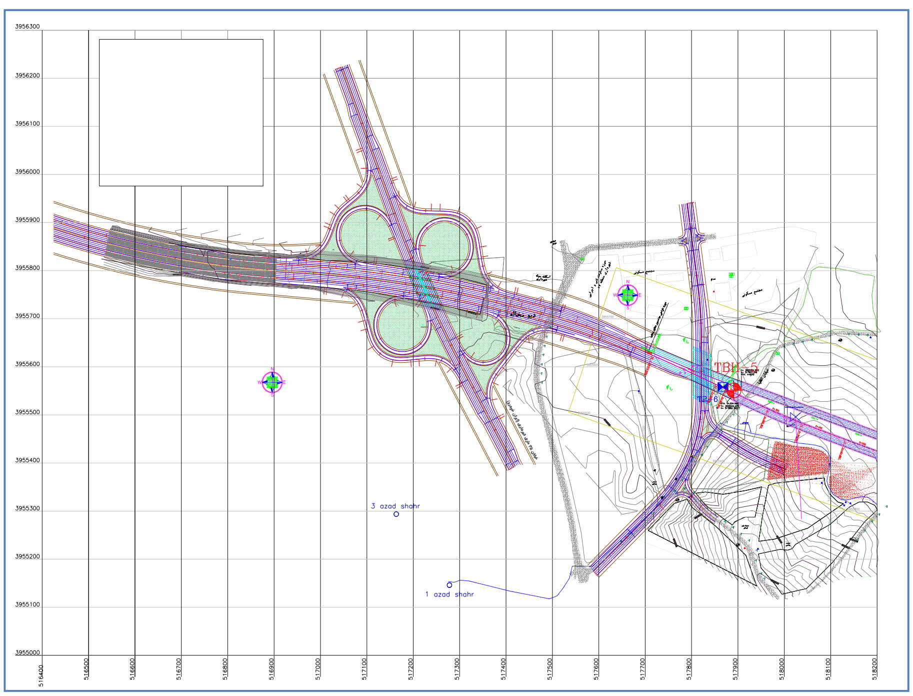

Figure 3-5 Location of the Township Relative to the Tunnel (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

3.1.2.5 Review the Underlying Conditions of the Hakim Tunnel Route

Based on the results of local investigations on boreholes, test pits, site and laboratory tests, a schematic of the geological and geotechnical characteristics along the longitudinal section of the tunnel route was prepared and is illustrated in Figure 3-6. Additionally, Figures 3-7 and 3-8 present a schematic of the transverse sections of the tunnel. It is observed that subsurface layers are formed from coarse alluvial deposits over layered by fill material and soil with plant roots of 1 to 2 meters in thickness. These sediments consist of alternating sandy layers with fine aggregates and some rubble belonging to Formation A**.** The layering of the sediments was steep and the slope was measured from layers located 15 to 20 degrees to the northwest. In the excavation of boreholes and the test pit, no empty space or cavity was encountered, but it is possible that such spaces could be located along the path to the duct of an abandoned aqueduct.

3.1.2.6 Groundwater status

In this project, groundwater was not encountered in any of the boreholes and wells excavated within the tunnel route. Even in deep drill holes, ground water was not seen in the Township (not even in the 100 m deep borehole). According to these studies, additional boreholes were considered within the Hakim Tunnel area and around it. Figure 3-9 shows the position of the boreholes. Based on the results, the depth of groundwater in the eastern part of the tunnel route is about 90 m and in the western parts, it is more than 100 m. Since tunnels are under a forest area and the overburden is not deep, the soil around the tunnels are moist. Thus, tunnels were constructed in a non-saturated environment.

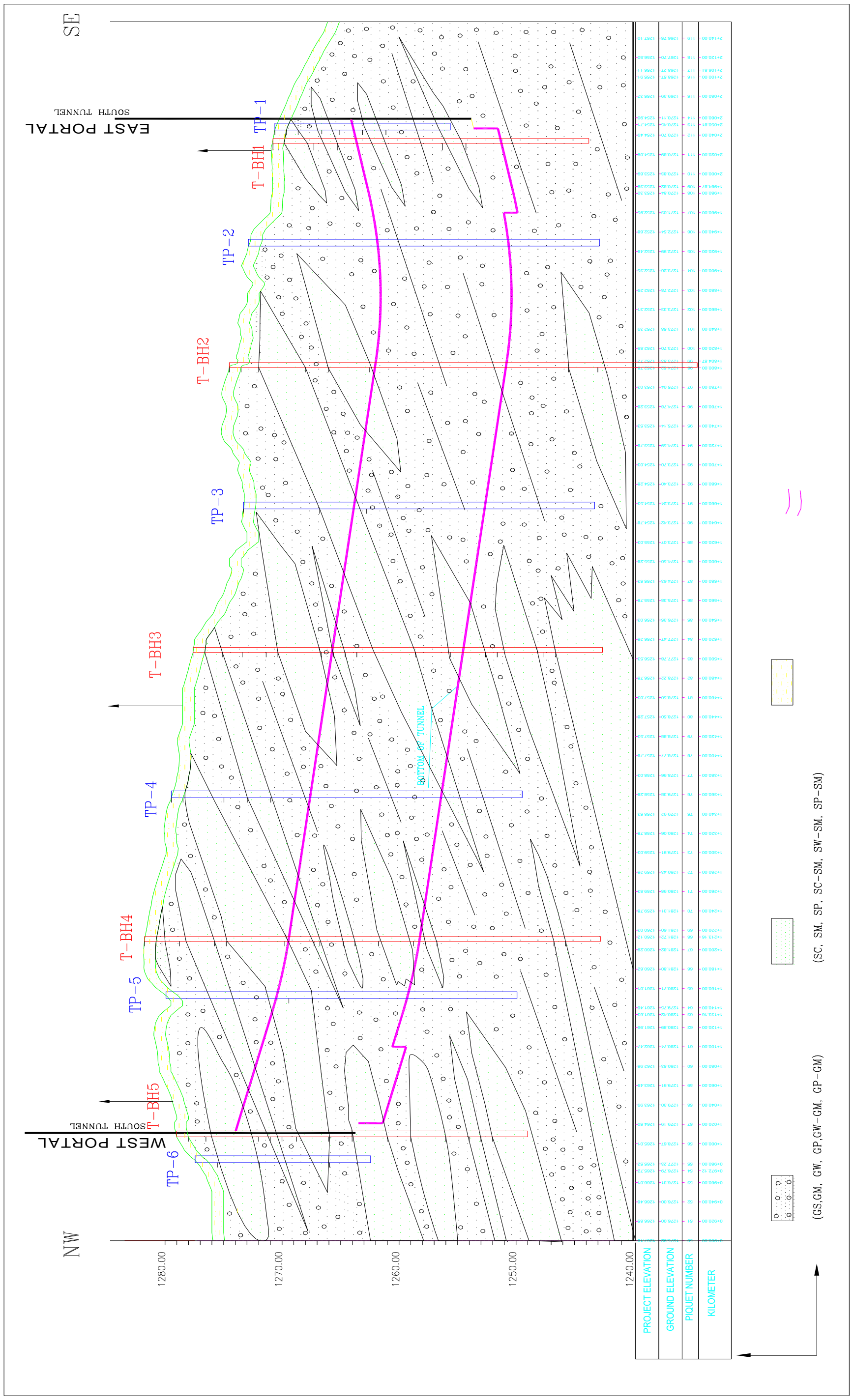

Figure 3-6 Geological Section along the Hakim Tunnel (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

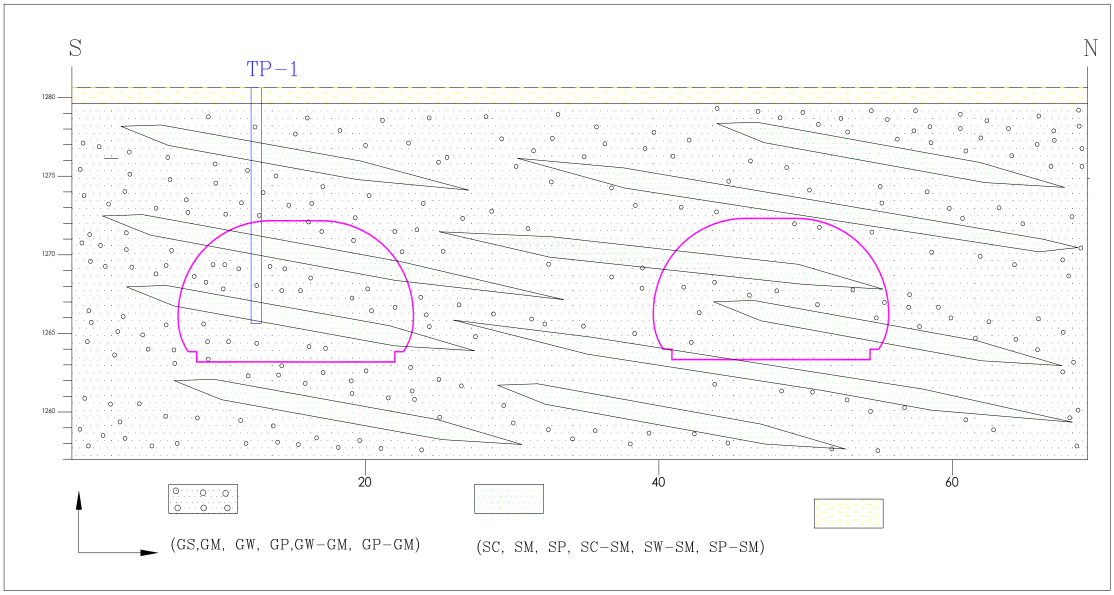

Figure 3-7 Transverse Geological Section of the Western Hakim Tunnel Portals (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

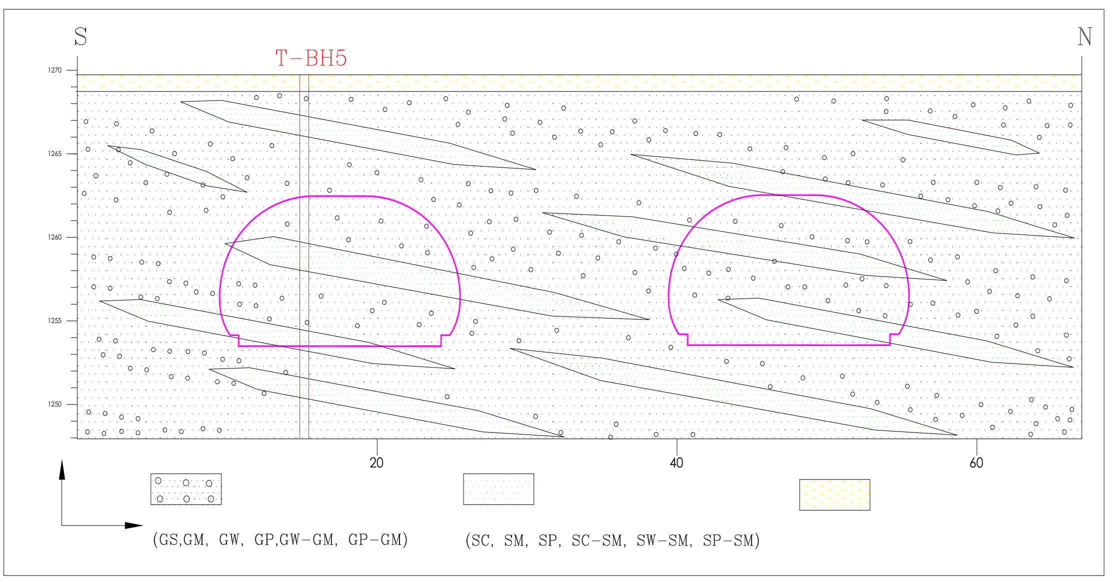

Figure 3-8 Transverse Geological Section of the Eastern Hakim Tunnel Portals (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

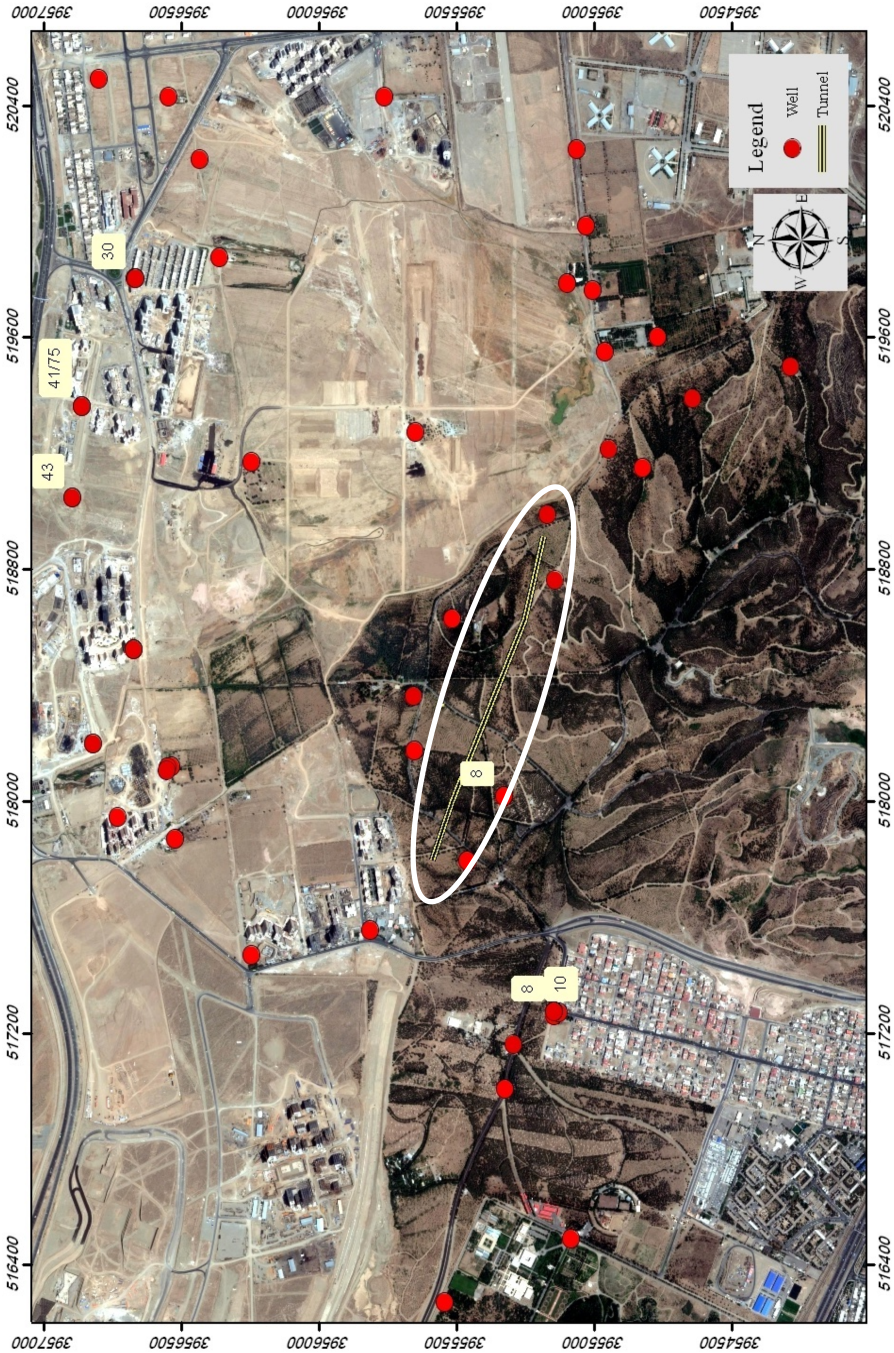

Figure 3-9 Location of Test Pits Located Around the Tunnel (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)
(Hakim Tunnel Route is illustrated with a Yellow Line)

3.2 Geotechnical Investigation in Hakim Tunnel Project

3.2.1 Results of Geotechnical Field Tests

In tunneling design and construction, geotechnical aspects are crucial. Engineers need to get accurate information for designing with a good margin of safety to reduce the geotechnical risks of the project. The geotechnical test results from the samples were obtained from field exploration. In the drilled test pit wells and holes, some on-site tests were performed, including standard penetration tests (SPT), plate loading, in-situ shear, tests field permeability tests, field density determination tests, dynamic tests (wavelength measurements), and perimetric measurements. The results of these tests follow:

3.2.1.1 Results of Field Density Tests, (γ, unit weight)

In the boreholes excavated in the tunnel route, a number of field density tests were carried out. Figure 3-10 shows their depth variations, where the unit weight of soils is measured between 1.64 and 1.99 (g/cm^3) and the unit weight of moist soil ranged between 1.81 and 2.17 (g/cm^3). In the Township study, the soil dry unit weight was 1.26 to 2.01 (g/cm^3), and the unit weight of moist soil ranged from 1.69 to 2.13 (g/cm^3). In the Chitgar Lake study, the minimum dry unit weight was 1.54 (g/cm^3) and the maximum was 2.2 (g/cm^3).

3.2.1.2 Results of Standard Penetration Test (SPT)

This test is one of the most commonly used tests to determine the physical and mechanical properties of soil layers. This test is in accordance with ASTM D1586-11 (ASTM, 2011). The number of blows required to penetrate each stage is recorded separately. The total number of blows required for the last two levels of infiltration is used as the N penetration number. During the test, whenever a distance of 15 cm requires more than 50 strokes, the test is stopped. In the borehole log. For example, if the test apparatus is penetrated 11 cm after it reaches more than 50 blows, the number of blows is shown as +50 cm.

The SPT numbers obtained from the experiments are generally more than 50. The SPT numbers are less than 50 with depths of about 30 in some boreholes. Thus, according to the qualitative description of soils according to Table 3-2 and based on the type of soil observed in the geological sections, it follows that the soil in the level of the tunnels is a very dense soil. Figure 3-10 shows the variation diagram of the SPT number relative to the depth of specimens on the Hakim Tunnel route.

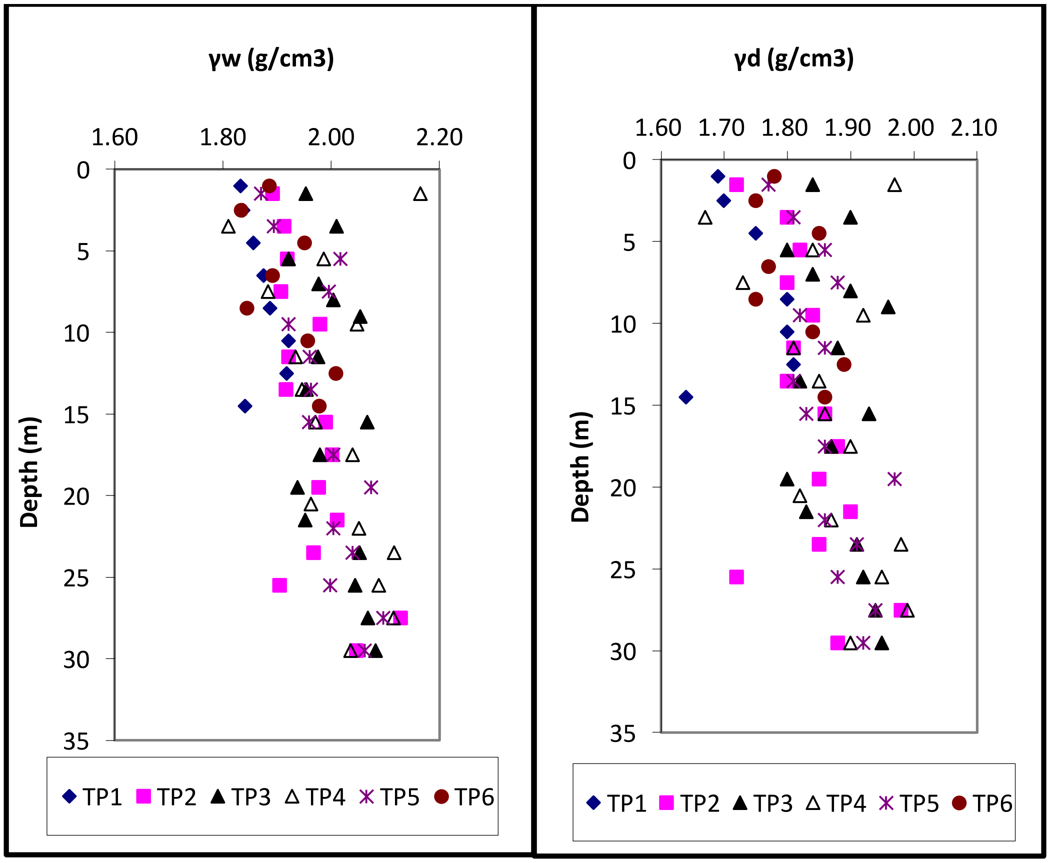

Figure 3-10 Changes in Dry Gravity and Wet Specific Gravity (Soil) Relative to the Depth in the Hakim Tunnel Range (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

Table 3-2 Condition of Soil Grain Density Based on SPT Number (AASHTO T307-99, 2003)

Description of soil condition	SPT
Very loose	0-4
Loose	4-10
Medium dense	10-30
Dense	30-50
Very dense	>50

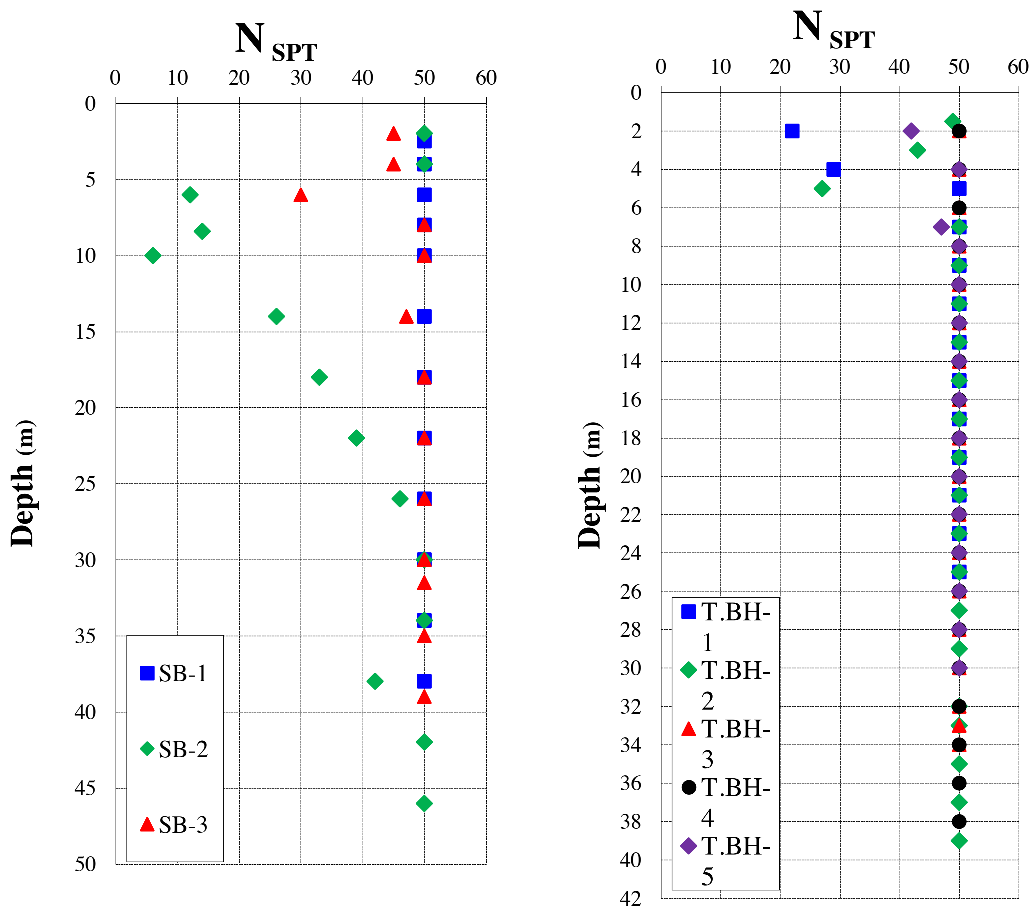

Figure 3-11 Variations of SPT Number (N) Relative to Depth; (Left) Chitgar Lake - Formation C, (Right) Hakim Tunnel - Formation A (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

3.2.1.3 Field Results of Permeability Tests, (Lufran Method)

The Lufran method is used to measure permeability in alluvial materials and crushed and weak rock layers. In the case where the test instruments are located beneath the surface of the ground water, the test can be carried out in three ways: rumbling, loading and constant load.

In the geotechnical studies of Chitgar Lake Dam construction, three different experiments were carried out. In the first experiment, 16 permeability tests were conducted in the drilled boreholes. Twelve Lufran experiments were conducted in the Hakim highway continuing project in the second experiment. Hakim complementary geotechnical studies were conducted in the third experiment. Regarding the results of the Lufran experiments, the permeability measured by the Lufran method in the C formation (Lake dam axis) was measured from 7.4E-03 to 1.0E-05 (cm/sec). The values in the Hakim tunnel route are in a much smaller range, varying from 2.5E-06 to 9.84E-06 (cm/s). The permeability of the A formation deposits in the tunnel route was about 10E-5 (cm/s), and in the formation of C sediments in the access ramps, the permeability was about 10E-4 (cm/s).

3.2.1.4 Results of Plate Loading Tests

By conducting the plate-loading test, the mechanical deformation properties of the layers are measured in situ, whereby the layers can be resisted and deformed. The results of the plate loading tests are used to determine the subgrade reaction modulus ($\mathrm{K_s}$) that is shown in Equation 1, the modulus of deformability of soil ($\mathrm{E_s}$) as shown in Equation 2, and the load capacity of each considered soil layer. The soil subgrade reaction modulus values in Township were obtained in the range of 13 to 30 ($\mathrm{kg\ /\ cm^3}$) and in the Hakim Tunnel route in a range between 12 and 40 ($\mathrm{kg\ /\ cm^3}$). The modulus of deformability in the Township is from 430 to 970 ($\mathrm{kg\ /\ cm^3}$) and varies from 380 to 1267 ($\mathrm{kg\ /\ cm^3}$) through the Hakim Tunnel route.

$$K_s = \frac{\Delta P}{\Delta S} \quad (1)$$

Where ΔP = load, ΔS = displacement, and K_s = Reaction Modulus

$$E_s = \frac{\Delta P}{\Delta S} \,.\, D \,.\, (1 - \vartheta^2).\, I \quad (2)$$

Where ϑ = Poisson ratio, D= sample diameter, I = moment of inertia, and E_s= modulus of deformability

3.2.1.5 Results of In-Situ Shear Tests

The in-situ shear test is a useful test for estimating the shear strength parameters of the soil in situ. This test is similar to the direct laboratory shear test, where more real and accurate estimation of soil parameters can be obtained from the use of larger and intact undisturbed samples. In this project, for the purpose of these experiments, a gallery with appropriate dimensions at the interested depths was excavated in one of the test pits, and then the experiment was carried out inside the gallery. Although soil of the area is mainly coarse grained, the alluvial formations of the project location are mainly cemented.

These tests were conducted in complementary geotechnical studies. The cohesion (adhesion) of soil along the tunnel route was of 0.14 to 0.87 ($kg\ /\ cm^2$). The internal friction angle was also determined in the range of 23 to 37 degrees. In the experiments conducted in the Township project, the adhesion value was obtained from 0.22 to 0.45 ($kg\ /\ cm^2$). The internal friction angle was also measured in the range of 31 to 41 degree. It is observed that the adhesion values and the internal friction angle in these two projects are very different.

3.2.1.6 Results of Pressuremeter Tests

Pressuremeter testing (Testometric or barometric) is one of the most useful field tests to determine the stress-strain behavior of the soil. These tests were performed inside boreholes using a cylindrical probe that can be swirled radially.

These experiments were carried out in the geotechnical studies of the continuation of the highway (Phase 1) and in the complementary geotechnical studies of the case study tunnel (Phase

2). Based on the results, the pressuremeter[1] modulus is calculated in the range of 544 to 1,812 $(\mathrm{kg/cm^2})$. In addition, the soil deformation modulus obtained from the results of the experiment is often in the range of 1,100 to 3,800 $(\mathrm{kg/cm^2})$.

3.2.1.7 Results of Seismic Tests

Seismic tests are based on the propagation of mechanical waves in an elastic environment. The wave produced by the seismic spring (such as hammer blow) reaches the receiver of waves (Geophone) and is then amplified and recorded by the seismic device. By measuring the velocity waves and the velocity of shear waves, as well as the density of the emission medium, the dynamic modulus of the soil layers can be calculated. Because in the seismic methods, the waves tend to be almost directly from the source to the receiver, they are more accurate than surface methods.

3.2.2 Results of Geotechnical Laboratory Tests

Laboratory experiments have been carried out on samples taken from boreholes and test pits to determine the physical, mechanical and chemical properties of soils in the laboratory. These tests include grain size distribution, hydrometric measurements, specific density determination, direct shear tests, tri-axial tests, permeability and soil chemical tests. In this section, the results of the laboratory experiments are summarized.

3.2.2.1 Results of Grain Size Distribution

In each of these projects near the Hakim Tunnel route, many soil classification tests were carried out. In the tunnels with wells drilled, the soils in the tunnel route are among the sandy soils and gravel with the classifications and frequencies shown in Figure 3-12. Figure 3-13 shows the graph of the liquid limit (LL) and the plasticity index (PI) of the fine-grained part of soil in the tunnel route.

[1] The pressuremeter test was developed by Louis Menard in 1957. This in-situ test provides the measurement of stress-strain response of soils. However, this modulus differs from the elastic modulus E which is a principal soil parameter.

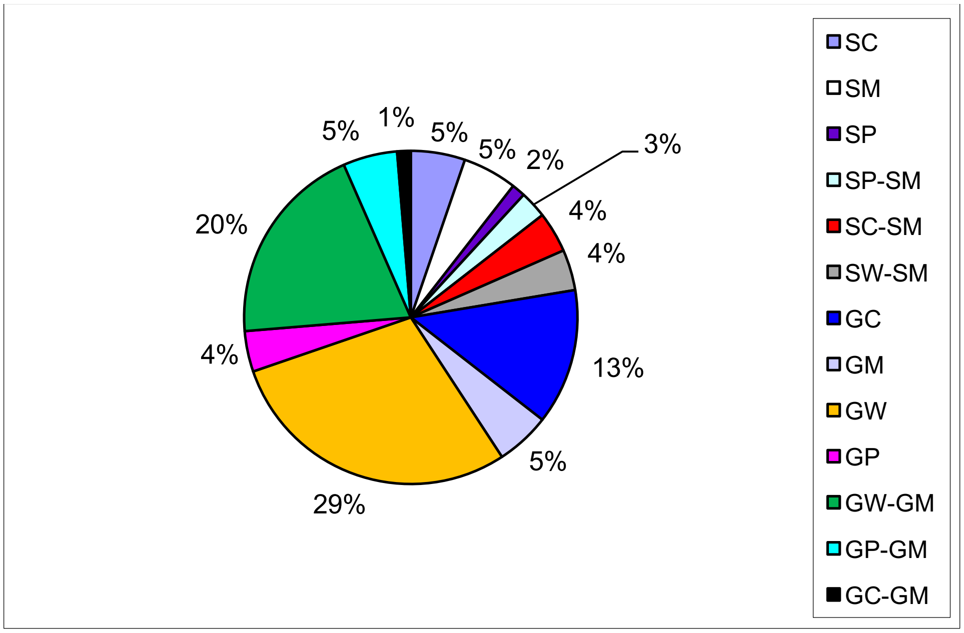

Figure 3-12 Frequency Distribution of Different Soil Classes Based on the Unified System of Classification in the Hakim Tunnel Route (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

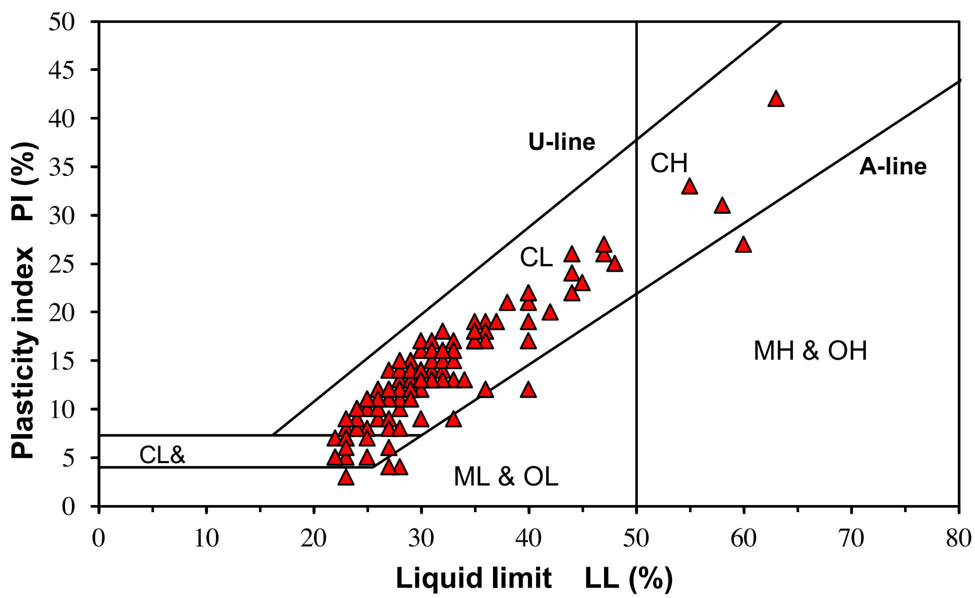

Figure 3-13 Liquid Limit – Plasticity Index Diagram for Fine Grained Part of Hakim Tunnel Route Soils (SAZBON Consulting Eng. Co.," Hakim Tunnel Geotechnical Report", Unpublished Report for Tehran Municipality, 2016)

3.2.2.2 Results of Moisture Content Tests

The soil in most parts of the case study location is coarse grained. It is not possible to obtain appropriate hand-drawn samples in order to determine the moisture content and density. Therefore, the determination of the moisture content and density were done separately on wax-plated specimens on the Hakim tunnel route. Samples of moisture samples were taken from machine boreholes, and a moisture content test was carried out on them. In the complementary geotechnical studies, a moisture determination test was done for the tunnel sample test pits. Changes in moisture content relative to depth are presented in Figure 3-14.

It is observed that changes in the moisture content are not high in depth and the soil moisture content along the tunnel route is 4 to 8 percent. Although localized, the moisture is increased in some areas due to irrigation of the Chitgar Forest Park trees. The minimum moisture content is 1% and maximum is about 16%.

3.2.2.3 Results of Specific Gravity of Solid Particles in Soil

These tests were performed according to ASTM D854-14 (2014). Given the fact that $\boldsymbol{G_s}$ is a function of soil minerals and the origin of all alluvium in the Hakim tunnel location is the same, it is possible to use the same numbers for the Hakim tunnel. More than 60 tests were carried out to determine the specific gravity of solid particles in the Township project. The specific gravity of solid particles in the soils of this region ranges from 2.57 to 2.71.

3.2.2.4 Results of Direct Shear Tests

Direct shear tests were performed in saturated conditions based on ASTM D3080 /D3080M-11 (2011). In the complementary geotechnical studies and the report of the continued Tunnel Phase 1, the number of direct shear tests were performed. In these experiments, adhesion ranged from zero to 0.45 $(\mathrm{kg/cm^2})$, and the internal friction angle was 32 to 41 degrees. In the Township project, 135 direct shear tests were conducted. Here, the adhesion was measured to be about 0.06-0.15 $(\mathrm{kg/cm^2})$ and the internal friction angle was in the range of 29 to 37 degrees. In the direct shear tests, the adhesion values ranged from 0.02 to 0.13 $\left(\frac{\mathrm{kg}}{\mathrm{cm^2}}\right)$, and the internal friction angle was in the range of 27 to 40 degrees.

3.2.2.5 Results of Density and California Bearing Ratio (CBR) Experiments

In order to investigate the possibility of using site soils in road operations, landscaping, etc., the density and California bearing ratio (CBR) tests were performed on samples taken from a number of test pits in the tunnel area. The optimum moisture content of soil was between 6.6% and 12.5%. The density of the maximum soils in the studied area varied from 1.96 to 2.10 $(\mathrm{g/cm^3})$. The CBR amount of soils varies from 6.8% to 19.1%, and the quality of materials for road construction was evaluated in a medium to good range.

3.2.2.6 Results of Tri-axial Compression Tests

In the Township project, several tri-axial CU tests were performed. In these experiments, the adhesion values ranged from 0.09 to 0.22 $\left(\frac{\mathrm{kg}}{\mathrm{cm^2}}\right)$, and the friction angle was in the range of 26 to 34 degrees.

3.2.3 Proposed Geotechnical Parameters

According to the results of in situ and laboratory tests carried out on the tunnel route as well as drilled boreholes in projects near the Hakim Tunnel site, the geotechnical parameters of different sedimentary units along the tunnel route were determined by using statistical surveys. The results of tests on Hakim Tunnel soil parameters are presented in Table 3-3.

Table 3-3 Final Geotechnical Parameters within the Case Study Tunnel Range

Name of Formation or Sediments	Surface fines	Formation **C** sediments	Formation **A** sediments
Dominant soil	Surface fines soils	Silty Sand and Gravel	Clayey Sand and gravel with Crushed rubbles
SPT (N)	30	>50	>50
Adhesion, **C** (Proposed for short term $(Kg/cm2)$	0.15	0.30	0.45
Adhesion, **C** (Proposed for long term $(Kg/cm2)$	0.075	0.15	0.25
Internal friction angle, **ϕ** (Proposed for short-term mode), degree	29	32	33
Internal friction angle, **ϕ** (Proposed for long-term mode), degree	31	35	37
Wet unit weight, **γ** $(gr/cm3)$	1.85	1.90	2.00
Saturation unit Weight, **γ** $(gr/cm3)$	2.00	2.20	2.20
Poisson ratio, **υ**	0.38	0.38	0.35
Modulus of deformability (short term) $\boldsymbol{E}$ $(Kg/cm2)$	550	700	900
Modulus of deformability (long term) $\boldsymbol{E}$ $(Kg/cm2)$	300	550	700
Modulus of deformability of unloading-reloading (short-term), $\boldsymbol{E}(Kg/cm2)$	1650	2100	2700
Modulus of deformability of unloading-reloading (long-term), $\boldsymbol{E}(Kg/cm2)$	900	1650	2100
Coefficient of permeability, $\boldsymbol{K}$ (cm/s)	10E-6	10E-4	10E-5

3.3 Hakim Tunnel Construction Method

The Hakim Tunnel is a two-way twin tunnel, consisting a 1,080 m long highway in each tunnel, one going east and the other going west with three lanes (3.5 m lines with 13.5 m road width) on each side, which extend across the width of each tunnel (Taromi 2015). The surrounding ground is granular semi-cemented granular soil. The method of construction was the New Austrian Tunneling Method (NATM) which is shown for Hakim tunnel in Figure 3-14.

NATM is a flexible tunnel construction method, which is based on following principles:

- In large span tunnels, staged construction is used,
- The supporting system is flexible and consists of shotcrete, shotcrete reinforcement (e.g., steel wire mesh), rock bolts or soil dowels, steel frames (e.g., H-sections of lattice girders),
- Ground-support interaction is monitored during construction using observation and instrumentation,
- As tunnel construction proceeds, the ground condition is observed and classified and any change in the ground condition may cause modification in construction method,
- The results of monitoring are used to control the construction integrity, verify the stability analysis and design of supporting system. Based on the results of instrumentation, Construction method and stages, supporting system, are modified, if needed.

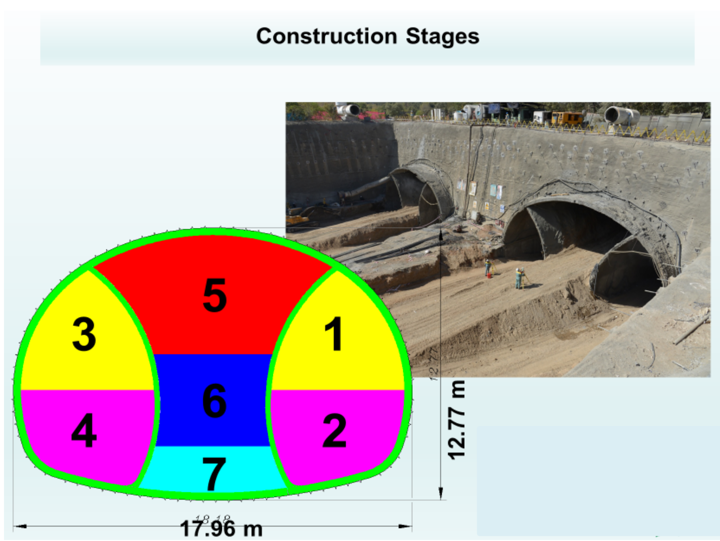

Figure 3-14 NATM Method for Hakim Tunnel Project

3.4 Summary and Discussions

1. The Hakim Tunnel Project is located in the *Chitgar Park Hills* in Tehran along an approximately East-West direction. Apart from the upper parts of the tunnel access ramps in the eastern and western portals, which are in geological formation **C**, the rest of the tunnel route lies within the sediments of formation **A**.
2. Subsoil layers of the site consist of coarse grain alluvial deposits (sand and gravel with some cobbles), along with a percentage of fine-grained (mainly clay) material. The dip of the sediment layering in the tunnel route is measured from 10 to 22 degrees. Meanwhile, the dip orientation of the layers is toward the northwest from 300 to 340 degrees.
3. According to the performed studies, there is no important fault crossing the tunnel route, but local fractures may be observed in some sections.
4. According to the recent exploration and boreholes, groundwater was not encountered. From the information of the nearest deep irrigation well in that area, the depth of groundwater is more than 90 meters.
5. Based on the results of standard penetration tests (SPT), soil in all boreholes has a very high density and except for a few cases in near surface, the N value in the rest of the cases is more than 50. Therefore, the tunnel is drilled in dense and hard deposits.
6. Based on the results of in situ tests, the dry unit weight of the samples was measured in the range of 1.64 to 1.99 (g/cm^3) and the moist unit weight was 1.81 to 2.1 (g/cm^3).
7. Based on the plate loading tests (with a 45 cm diameter plate) conducted in the project area, the subgrade reaction modulus was obtained in the range of 12 to 40(kg/cm^3).
8. Based on the results of in situ shear tests, soil adhesion was measured from 0.14 to 0.87 (kg/cm^2) and the degree of internal friction angle was measured in the range of 23 to 37 °.
9. According to Iranian earthquake building code UBC 2800 (BHRC, 2007) and results of seismic tests, the project is located in a Type II-B zone, medium to high seismic zone.
10. Based on Pressuremeter tests, the pressuremeter modulus is calculated in the range of 544 to 1812 (kg/cm^2).

11. Based on permeability field tests, the average formation permeability along the tunnel route is estimated as 5E-10(cm/s). In some of the relatively clean sand layers, the magnitude of permeability seems to be greater.
12. Based on grain size distribution conducted in complementary geotechnical studies of the Hakim tunnel, about 50% of the project area deposits are classified as GW and GW-GM soils. However, in local observation of soil layers in the portals area, the amount of fine-grained soils was higher and the classification of most soils seems to be GM and SM.
13. In laboratory rapid direct shear tests, adhesion ranges from zero to 0.45 (kg/cm^2) and the internal friction angle of 32 to 41 degrees is obtained. The low values of adhesion may be due to the disturbance of tested samples.
14. Based on the results of the compaction tests, the optimum soil moisture content is in the range of 6.6% to 12.5% and the maximum unit weight of soils in the studied area varies from 1.96 to 2.10 (kg/cm^3).
15. According to the results of CBR tests, the amount of CBR of soils varies from 6.8% to 19.1%. Therefore, the quality of materials for road base construction is evaluated between medium and good.

CHAPTER 4

GEOTECHNICAL ASSESSMENT OF THE CASE STUDY PROJECT

To protect *Chitgar Forest Park* in Tehran, Iran, Hakim highway route was converted to underground twin tunnel along this park. The geotechnical investigation of this project was part of the main initial investigation of the western zone of the Hakim Highway project. The Hakim tunnel project is constructed with a Design-Build (DB) contract. Very limited geotechnical information on the tunnel part was available before the tunnel contract. Geotechnical information from three other studies of adjacent projects were available before the contract, but they were not part of the bid documents. The complementary geotechnical investigation was planned and conducted later by the DB contractor.

In the following sections, the available data before and after the contract are analyzed according to the main items of the ASCE *Geotechnical Baseline Report* (GBR), which provides the following information:

- Source of geological and geotechnical information,
- Project in geologic setting,
- Previous construction experience,
- Ground characterization,
- Design consideration, and
- Construction consideration.

The geotechnical risk sharing in this project was not clear before the contract. The owner later agreed to share part of the risk in accordance with the geotechnical information obtained from the complementary study after approval of this study by his supervising consulting engineering company.

One purpose of this thesis research was to analyze and evaluate the available geotechnical information and parameters of the Hakim Tunnel Project based on the GBR standard. The main risk factors of this project were identified, introduced and analyzed based on the project conditions. The cost overrun was also analyzed and estimated.

4.1 Qualitative Geotechnical Analysis of Hakim Tunnel Based on GBR

In Chapter 2, it was determined which geotechnical factors and parameters are most important in tunneling design and construction. Based on this thesis's Hakim Tunnel case study, the geotechnical investigation of the Hakim Tunnel Project before and after the contract was discussed in Chapter 3.

The GBR of every project is a report to express necessary information in contract documents to reduce contract problems and disputes. As a contract document, it also serves as a guideline to define geotechnical issues and risks for a tunnel project to clarify unforeseen ground conditions, which are usually a common source of uncertainty in tunneling projects. A GBR helps the owner to reduce uncertainty in contractual terms for conflict resolution and prevents the owner from overpaying through the safeguard of contractual base estimates.

There was no specific GBR for this project. In this research, the actual Hakim Tunnel Project contract document was studied and compared item by item with ASCE's GBR standard. Finally, any shortcoming and deviation and approach during this process, before and after the contract will be discussed.

In the following sections, GBR's major factors are divided in to parts and compared with Hakim Tunnel Project'sDesign-Build (DB) Contract and investigation documents in each subtopic, separately.

4.1.1 GBR - Source of Geological and Geotechnical Information

Hakim Tunnel Project Contract: Geological and geotechnical information in contract documents were from limited preliminary investigation and some historical precedence. These data were not conclusive and further investigation was suggested in the contract to be conducted by DB contractor.

Analysis: Source of geological and geotechnical information should be provided in any type of contract. This prevents replication and makes it easier to get first-hand information quicker and more efficiently. It also ensures the integrity and accuracy of the data. These data help DB contractor's engineers to properly plan and conduct complementary and required geological and geotechnical investigations. Regarding these principles, one of the major weakness of this contract was lack of any official reference to the Geotechnical Data Report (GDR). The GDR had some shortcomings and even if it was included in the contract document—even in a very limited format, it would have lacked information in some parts.

4.1.2 Project Geologic Setting

Hakim Tunnel Project Contract: The report of primary geological and geotechnical investigations (Limited GDR) included information on general Tehran alluvial geological formations. General groundwater settings, original deposits and some geological maps were provided in the project's primary geological and geotechnical report. Initial limited exploration and testing programs were briefly included in that report. Surface development, topographic, and environmental conditions along the tunnel route were included in the report. Due to the limited exploration before the contract, in the geological profiles along the tunnel alignment, limited boreholes were shown; thus, the stratigraphy of soil/rock units was not accurate.

The geologic setting of the Hakim tunnel alignment was summarized in general technical documents but in some parts, the contract lacked accurate information specifically in specific geological and groundwater settings with any reference to GDR.

Analysis: As described in previous sections, the Hakim tunnel project had a Design-Build contract; therefore, before the contract, a limited investigation was conducted. Based on historical data and information from primary and previous resources, Tehran geology was defined as consisting of four different types of alluvial formations. Among those formations, formations A and C are dominant in the Hakim tunnel route. Geologic formation data is one of the important elements in geological settings are needed in any GDR. GDR information should be the main resource for GBR that helps all parties to have identified data for project design, management and risk sharing. In addition, by using these data, geotechnical and design engineers decide what type and how many tests are needed to obtain proper and required information for design and construction purposes. However, in the Hakim Tunnel, the geological setting was not properly included in a GDR format;

thus, some required important information was not included in the bid contract. As a result, some information was not complete in contract documents.

Lack of accurate and sufficient information in bid documents causes the bidding contractors to be cautious and offer a higher bid price.

4.1.3 Previous Construction Experience

Hakim Tunnel Project Contract: Previous Construction Experience in this project can be described in two ways: 1) urban tunneling experience and 2) nearby projects that had some similarity with the Hakim Tunnel project.

There was no information about previous construction experience in contract documents. Experience and information of three other adjacent projects were available but not included in contract documents. These projects were:

1) Extension of Hakim highway (about 11 Km),

2) Chitgar Lake and dam, and

3) Township.

These projects were near the Hakim Tunnel Project. They were constructed before the Hakim tunnel. The geotechnical information and construction experience of these projects were available for the contractor and later were used in planning complementary geological and geotechnical investigation.

Analysis: One of the main issue is that these three projects are not tunnel projects. Invited bidders had metro and highway tunnel construction experience in Tehran. Similar tunnel experience and preliminary geotechnical information would have helped the DB contractor to have better planning and approach for the design and construction of the Hakim Tunnel project. The owner and his supervising consulting engineering company had good previous experience in both metro and urban highway tunnel projects. The designer and the contractor's construction teams also had proper experience working on another Tehran highway tunnel.

The owner of two of the adjacent projects (Extension of Hakim highway and Chitgar Lake and dam) was the Tehran municipality; therefore, they officially provided information on other projects in the tunnel bid documents.

4.1.4 Ground Characterization

Hakim Tunnel Project Contract: As indicated in previous sections, the geotechnical investigation was limited before contract negotiations started. This limited information is summarized in general technical documents and discussed briefly in Chapter 3 of this thesis.

Analysis: Knowing the ground condition of the project is crucial. It is very important to determine when and how these data became available and who was in charge of these tests and the investigation before starting the project. In the Hakim Tunnel Project, a complementary geotechnical investigation was carried out after the contract was awarded and before the start of construction. With the information from the complementary geotechnical investigation and their experience, the design and construction teams cooperated to prepare a suitable design and construction method. They were together all through the project, so any change of ground was assessed on site and any needed modification in design or construction method were done. In general, the design was overdesigned.

4.1.5 Design Consideration

Hakim Tunnel Project Contract: In a contract document, no specific design consideration was presented; only design criterion and designing codes of practice were emphasized. Low overburden was one of the main concerns for the Hakim Tunnel.

Analysis: Tunnel is located in *Chitgar Forest Park*; therefore, surface ground settlement was not a concern. There were two main concerns in this site, low overburden and special geological features. Low overburden prevents creation of soil arching over the tunnel crown; therefore, in designing the support system, total overburden weight should be considered for loading the crown support.

In the upper layers of the alluvial formations of Tehran, thin layers of either loose sand, or clay lenses occurred. In some locations, the presence of large boulders (over 0.5 m^3) was also possible. Results of geotechnical investigation showed thin lenses in some locations, but there was no indication of boulders in the area.

4.1.6 Construction Consideration

Hakim Tunnel Project Contract: In a contract document, no specific construction consideration was presented.

General and specific construction methods were included and sequences of construction were provided in drawings of bid documents. Since there was no official GBR in the bid documents, to make bidding contractors obligated to abide by some constraints, participating DB contractors were asked to provide detailed construction methods, predicted difficulties and constraints of the project with their bid documents. This was to motivate bidder recommendations on any possible ground improvement, modifications, or groundwater control methods in their bid documents.

Analysis: As indicated above, there were two main technical concerns on this site; low overburden and special geological features. Low overburden prevents creation of soil arching; therefore, in the excavation phases, major attention had to be paid to prevent extended overhead breaks and local soil collapses from the crown and sides. Thin weak layers (e.g., soil lenses) were construction concerns. In critical cases, special measures such as forepoling[2] may be necessary to prevent soil collapses when thin layers of loose sand were encountered in crown.

The natural groundwater level was deeper than the tunnel project level; therefore, there was no major concern regarding groundwater flow in this project. Subsurface water from Forest Park was the only water that could affect the construction sequences.

4.1.7 Conclusion of Analysis

After the supervising engineer and owner approved results of later complementary investigations, unofficially the documents on these investigations became much like a GBR during the construction phase. This was in accordance with ASCE (2007) GBR guidelines. Based on the preliminary information and experiences, DB contractor suggested that required equipment,

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[2] A method of advancing a tunnel in loose, caving, or watery ground, such as quicksand, by driving sharp-pointed poles, timbers, sections of steel, or slabs into the ground ahead of, or simultaneously with, the excavating.

machinery, and specialized personnel for this project be included in his bid and later in contract documents. After a complementary investigation, their list of equipment, machinery and specialized personnel were updated.

4.2 Determination of Economic Impact of Geotechnical Study

Study of the cost of geotechnical parameters of the Hakim Tunnel project was based on information from contractor invoices. Three main categories of geotechnical investigation in Phase 1 and Phase 2 are as follows:

- Geotechnical Investigation Operation
- Geotechnical Field Test
- Geotechnical Laboratory Test

Investigation cost before and after contractual agreements were finalized for mentioned items are illustrated in Tables 4-1, 4-2, 4-3 and 4-4.

Table 4-1 Geotechnical Investigation Operation Cost (Contractor's Invoice) ($)

Geotechnical Investigation Operation	Phase 1 (Before Contract) *	Phase 2 (After Contract) *
Boreholes	30,000	105,000
Test Pits	14,000	46,000
Sampling	9,000	19,000
TOTAL	**53,000**	**170,000**

* Based on 2016 US$ exchange rate

Table 4-2 Geotechnical Field Test Cost (Contractor's Invoice) ($)

Geotechnical Field Test	Phase 1 (Before Contract) *	Phase 2 (After Contract) *
Field Density Test	15,000	30,000
Standard Penetration Test	15,000	23,000
Permeability Test	N/A	25,000
Plate Loading Test	N/A	34,000
In-Situ Shear Test	9,000	19,000
Pressuremeter Test	N/A	26,000
Seismic Test	N/A	22,000
TOTAL	**39,000**	**179,000**

* Based on 2016 US$ exchange rate

Table 4-3 Geotechnical Laboratory Test Cost (Contractor's Invoice) ($)

Geotechnical Laboratory Test	Phase 1 (Before Contract) *	Phase 2 (After Contract) *
Grain Size Distribution	N/A	25,000
Moister Content Test	N/A	14,000
Specific Gravity of Solid Particles	N/A	17,000
Direct Shear Test	30,000	N/A
Density and CBR Test	11,000	24,000
Tri-Axial Compression Test	N/A	17,000
TOTAL	**41,000**	**97,000**

* Based on 2016 US$ exchange rate

After breakdown of each geotechnical items' price data, the results are presented in Table 4-4.

Table 4-4 Total Cost of Geotechnical Investigation for Phases 1 & 2 ($)

Geotechnical Investigation	Phase 1 (Before Contract) *	Phase 2 (After Contract) *
Geotechnical Investigation Operation	53,000	170,000
Geotechnical Field Test	39,000	179,000
Geotechnical Laboratory Test	41,000	97,000
TOTAL	**133,000**	**446,000**
Phase 1 + Phase 2	**579,000**	

* Based on 2016 US$ exchange rate

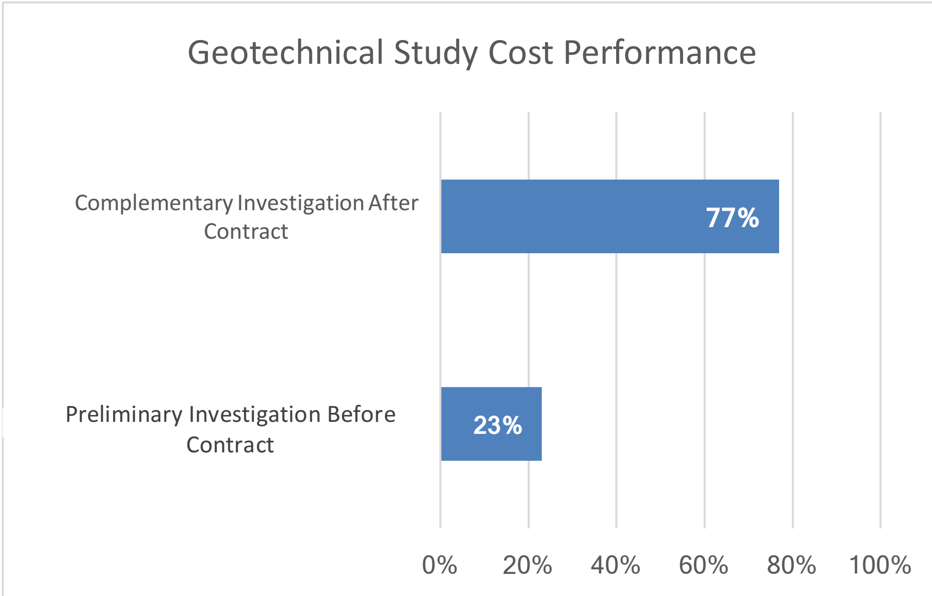

Figure 4-1 Geotechnical Investigation Cost Performance

Figure 4-1 compares before and after geotechnical investigation costs based on total percentages of preliminary and complementary project costs, respectively. Total cost was $105 M. Thus, in this study, 77% of geotechnical investigation was done after contract.

To verify results of stability analyses and design of Hakim Tunnel project, instrumentation and monitoring were planned, designed and implemented. Therefore, geotechnical monitoring and instrumentation are considered as part of the geotechnical study during construction. Monitoring and instrumentation during the construction can be considered as part of the post-geotechnical study. Table 4-5 demonstrated all costs of geotechnical studies for the Hakim Tunnel project.

Table 4-5 Total Costs of Geotechnical Investigations for Hakim Tunnel Project ($)

Geotechnical Investigation of Hakim Tunnel Project	**Cost***
Preliminary Investigation Before Contract	133,000
Complementary Investigation After Contract	446,000
Monitoring and instrumentation	174,000
Total	**753,000**

* Based on 2016 US$ exchange rate

The US Committee on Underground Technology of the National Science Foundation suggests about 3% to 5% of contract cost should be spent for geotechnical investigation of complex tunnel projects. In this tunnel project case study, total cost of this study was about $753,000, which is about 0.7% of the total project cost of $105 M).

This implies that the geotechnical investigation of the case study project was not based on GBR nor on the total cost of the geotechnical investigation before and after contract, if geotechnical investigation was conducted before the contract, the bid and contract prices could have been less and the project would have cost about 5 to10% less.

4.3 Discussion on Major Geotechnical Factors

This section will discuss about the major challenges of the Hakim Tunnel project which is reported as a document based on geotechnical parameters and construction issues. These issues follow:

- Overburden *(γ.z)*
- Soil Strength (Adhesion) *(C)*
- Soil Modulus of Deformability *(Es)*

Monitoring consisted of geodetic, tunnel convergence at every stage of construction and Multipoint Borehole extensometers from the ground surface. They were planned, designed and implemented. The results of monitoring showed that there was no stability problem. Usually the deformations (i.e., convergence and ground settlement) were less than the results of initial stability analyses. This showed the design and construction to be somehow conservative and overdesigned.

To prove this conclusion and verify the impact of sufficient geotechnical investigation before the contract according to GBR, a finite element modeling by PLAXIS was conducted for finding load distribution and magnitude, and cost estimation in this thesis. It showed that the contractor's design was overdesigned. Although the complementary geotechnical investigation provided more accurate results, the DB contractor did not optimize the design and tried to keep the initial contract price. If the owner had sufficient geotechnical information before the contract, the bid price would have been realistically lower and construction costs would have been less.

The results used in cost estimation of actual conditions are compared with project cost where the design was conservative. In this analysis, the stages of construction, including excavations and initial supporting system and final lining (Figures 4-2, 4-3), is numerically modeled.

Figure 4-2 Staged Construction (Excavation and Initial Supporting System)

Figure 4-3 Final Lining of Tunnel

The results of analysis show the influence of variation in soil modulus of deformability *(Es)* for this project's case study.

Soil Modulus of Deformability (Es)

Lower *Es* means higher deformation and possible ground collapse (William, 1998). In Phase 1, very limited testing was conducted and the contractor took very inflated values for cost estimates based on the low *Es.* In Phase 2, the plate load tests were conducted and *Es* values were determined, which were higher. Since the contractor had made his cost based on contract estimation, and it was on inflated values of parameters, it was considered overdesign and construction cost was high.

4.4 Questionnaire from owner and contract and consulting engineer‘s representatives

Some technical and professional questions were raised and the owner, consulting engineer and contractor's representatives made their responses. The responses were studied, analyzed and concluded. The summary of the responses follow:

Questionnaire:

1. *What was the base or standard procedure and outline for geotechnical investigation before the contract?*

A1- There was no standard procedure or outline for geotechnical investigation before the contract. A consulting geotechnical engineering firm initially studied the project. In his scope of work, he should:

- Design the best route for the highway considering environmental aspects,
- Conduct a preliminary limited geotechnical study of the route

Based on preliminary limited geotechnical study and limited information from the geotechnical investigation of adjacent projects, the bid documents were prepared. One of the main reasons for conducting a limited geotechnical investigation was the type of contract. The project contract was a design-build contract. Therefore, it was expected that the contractor would conduct the main geotechnical investigation after the contract was awarded.

2. *Why did the owner decide to have five boreholes before the project contract?*

A2- Based on the route and preliminary geological study, the geotechnical engineering firm decided to have only five boreholes in the preliminary geotechnical investigation.

3. *Why did the owner, supervising engineer and design-build contractor feel they needed more geotechnical investigation?*

A3- The geotechnical information based on the pre-contract study was not sufficient.

In the contract document, it was indicated that a thorough geotechnical investigation is needed after the contract. The contractor's design team and the owner's supervising consulting engineering firm found that available information was not enough for the design of the tunnel.

4. *How was the Geotechnical Baseline Report used in the geotechnical investigation before and after the contract?*

A4- The Geotechnical Baseline Report was not considered before or after the contract. Some parts of the preliminary and complementary geotechnical investigation were in the GBR scope, but they were not based on it.

5. *What were the main geotechnical parameters that could influence the bid price before contract?*

A5- According to the geotechnical investigations, stability analysis and design results, the following parameters were most important and effective in the design and construction of Hakim Tunnel:

- Modulus of deformability of soil
- Shear strength parameters: adhesion, friction angle
- Wetness of soil
- Existence of weak layers and zones

Besides the geotechnical parameters, low overburden of tunnel route is one of the main parameters that affects bid price. If the geotechnical information were sufficient and accurate before the contract, the bidders would have estimated much more realistically and would have lowered the price.

6. Why was NATM chosen as the construction method?

A6- NATM is a tunneling method where a wide tunnel in weak ground, is usually constructed in stages. The supporting system is flexible and ground-support interaction of the tunnel is monitored by instrumentation and design so the construction method could be optimized.

Hakim Tunnels are wide-span highway twin tunnels. The surrounding ground is soil. The soil is cemented granular soil, but due to low overburden, tunnels had to be constructed in stages. The initial supporting system was shotcrete, steel wire mesh and lattice girder frames, which make a flexible supporting system. The tunnel construction was monitored by an extensive instrumentation system.

7. Who was the responsible body for the design of Hakim Tunnel?

A7- The contract was a Design-Build Contract. In this type of contract, the contractor is responsible for the design.

8. What were the geotechnical risk factors in the Hakim tunnel project?

A8- The risk factors are: low shear strength, low overburden and variable geological conditions

9. How were the risk factors identified?

A9- The risk factors were identified based on the overall geotechnical investigation, topography and Hakim Tunnel condition.

10. How were the risk factors managed?

A10- Since the contract documents did not contain a GBR, the construction risk was not managed properly. Although the contract price was not optimum, the owner took the major risks. This was the weak point of this project.

11. How much could they have saved in project cost?

A11- It is estimated that if a good and thorough geotechnical investigation had been conducted before the contract was signed and if a related Geotechnical Baseline Report had been included in the bid documents, a substantial cost saving could have been achieved.

4.4.1 Summary of Questionnaire

This questionnaire clarified the geotechnical investigation process and helped for better understanding about geotechnical situation of the project. Important geotechnical factors were recognized that caused risk challenges in this project. Based on the answers, geotechnical investigation in this project not only did not follow geotechnical standards such as ASCE-GBR nor sufficient geotechnical information exist before contract. As a result, it caused the higher bid price and increased in total cost of the project.

4.5 Finite Element Method Analysis and Cost Estimating of Final Lining Support

Based on insufficient geotechnical information and lack of accuracy of results in the Hakim tunnel project before the contract, the contractor used geotechnical data, which was provided by the owner before the contract. According to those data, the contractor's design was overdesigned. To prove the overdesign assertion, numerical modelling by PLAXIS finite element software was conducted.

PLAXIS software is a geotechnical analysis software for analyzing variable soil conditions and construction stages based on the finite element method. In PLAXIS, the contractor considers three important geotechnical parameters, soil adhesion shear strength (C), friction angle (ϕ) and soil modulus of deformability (Es) in stability analysis and design. In the numerical analysis conducted in this research, the values of soil adhesion strength (C) and friction angle (ϕ) is considered the same as contractor. The sensitivity analysis is based only on the soil modulus of deformability (Es) in numerical modelling.

4.5.1 Analysis for Tunnel Support System Using Numerical Modeling

The result of instrumentation station monitoring showed a settlement of approximately *41 mm*. The settlement of tunnel-based stability analysis using numerical modeling before construction showed *67 mm* in the same location in the initial design. If the engineers of a DB contractor had back analyzed that location based on a *41 mm* convergence, they could have obtained a lighter supporting system.

In this research, the potential optimization of the final implemented lining design is usually defined as reinforced concrete for the operation period as cast in place concrete with an initial supporting system design. It is used for soil stability during tunnel construction, which consists of layers of shotcrete, reinforcing steel wire mesh, bolting, and steel frames (H section and lattice girder). Soil settlement is compared based on data obtained from the following sources:

- Ground settlement based on real instrumentation measurement
- Ground settlement based on numerical modelling by PLAXIS modeling

The contractor's bid price was based on initial geotechnical investigation before contract, which used *Es*, C and ϕ as follows:

Es = 1000 kg/m^2 = 100 *MPa*

C = *0.*35 kg/cm^2 = 35 *MPa, and*

ϕ = 30 *degrees*

Back analyses were based on the observed ground deformation. The measured ground settlement was 41 mm. Results of numerical back analyses modeling showed that the *Es* value was about 1.75 time higher than the initial values (*Es = 1750* $\frac{kg}{m^2}$ = 175 *MPa*), which shows that the design was conservative.

The result of the numerical modeling analysis is vertical ground settlement, contour of ground deformation and internal loads (axial forces, bending moment, and shear forces). The maximum settlement of tunnel on top of tunnel arch, in the final lining structure system is provided in two forms: First, results of analysis were based on the soil parameters of a geotechnical study that was obtained before the contract was signed. Second, based on results of numerical back analysis as verified by the monitoring measurement and results were compared.

The results demonstrate the importance of a thorough geotechnical investigation in the initial phase of every tunneling project before the contract to achieve a more realistic bid price. Figures 4-4 through 4-11 illustrate the result of numerical modeling.

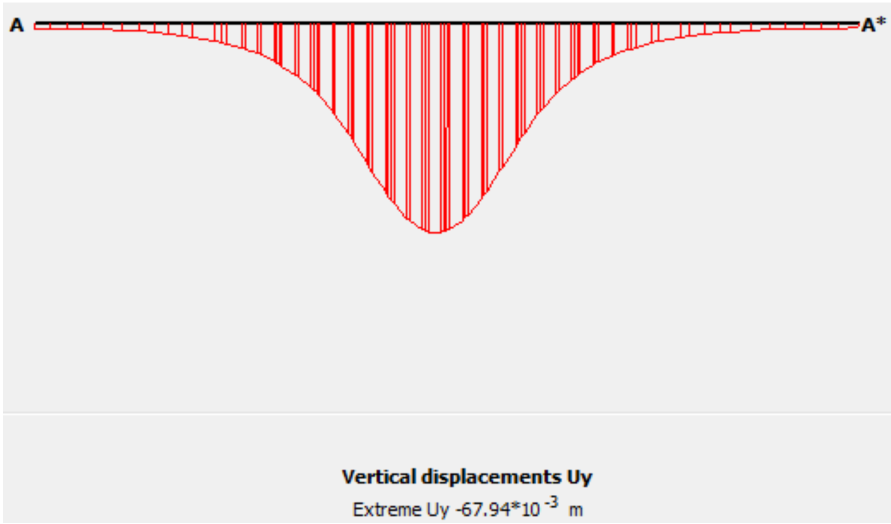

Figure 4-4 Ground Settlement Diagram above Tunnel – Modeling of Final Lining Structure Based on Initial Geotechnical Investigation

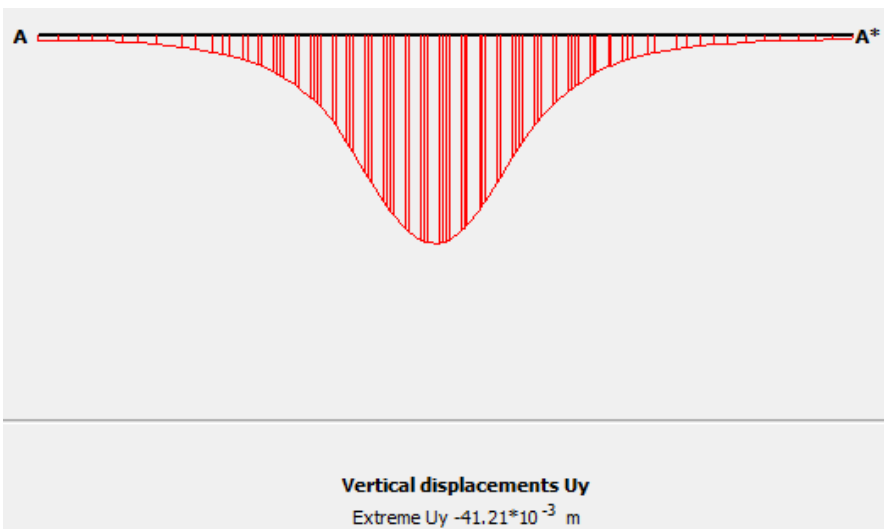

Figure 4-5 Ground Settlement Diagram above Tunnel – Back Analysis by Modeling of Final Lining Structure Based on Ground Monitoring

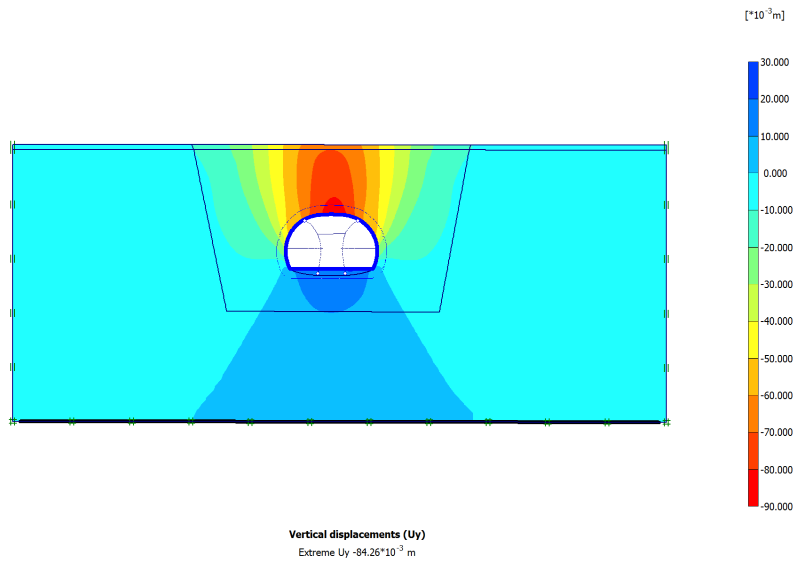

Figure 4-6 Soil Deformation Contour - Modeling of Final Lining Structure Based on Initial Geotechnical Investigation

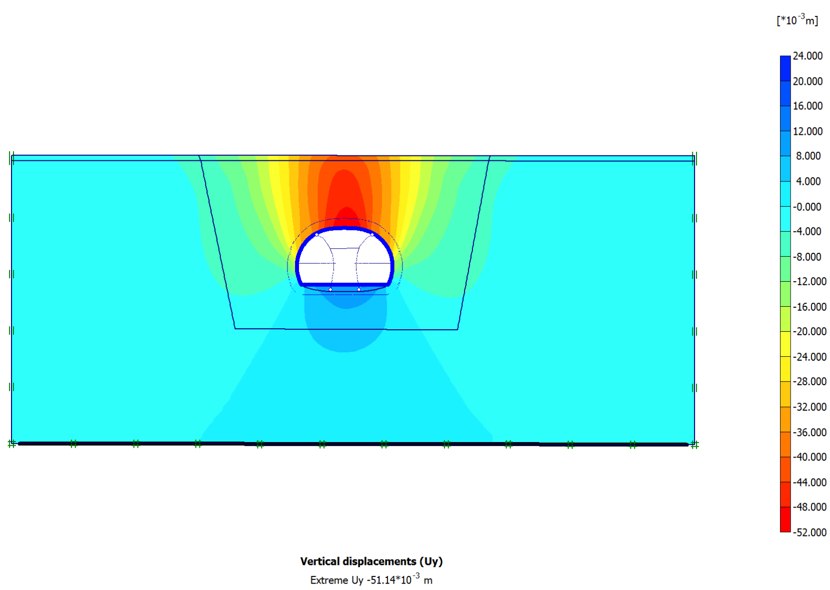

Figure 4-7 Ground Deformation Contour – Back Analysis by Modeling of Final Lining Structure Based on Ground Monitoring

The results show that the ground settlement based on data from the initial geotechnical investigation is about 66% is greater than the values obtained from the back analysis models based on the actual monitoring measurements (i.e., 68 mm, 41 mm). Similarly, the ground deformation contour above the tunnel base on the data from the initial geotechnical investigation was about 65%

greater than the values obtained from back analysis models based on the actual monitoring measurements (i.e., 84 mm, 51 mm).

Figure 4-8 Bending Moments Diagram - Modeling of Final Lining Structure Based on Initial Geotechnical Investigation

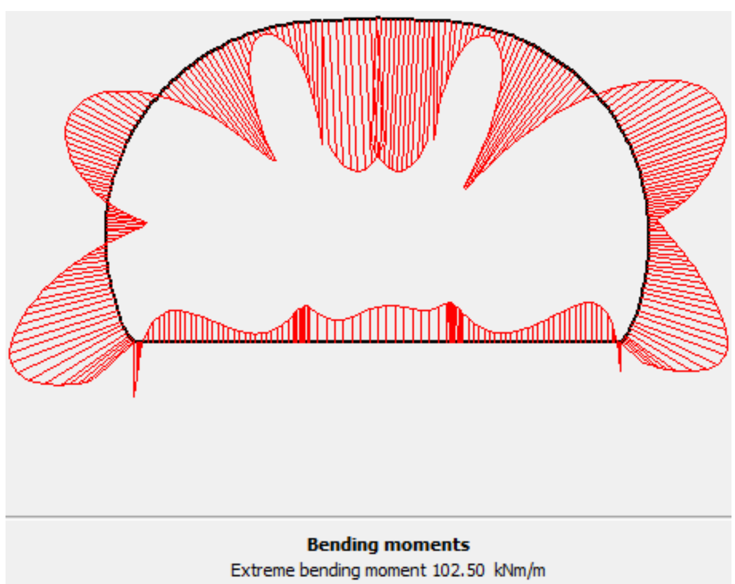

Figure 4-9 Bending Moments Diagram – Back Analysis by Modeling of Final Lining Structure Based on Ground Monitoring

The results show that the maximum bending moments base on the data from the initial geotechnical investigation is about 42% greater than the values obtained from back analysis models based on the actual monitoring deformation measurements (i.e., 145.54 kN.m, 102.5 kN.m).

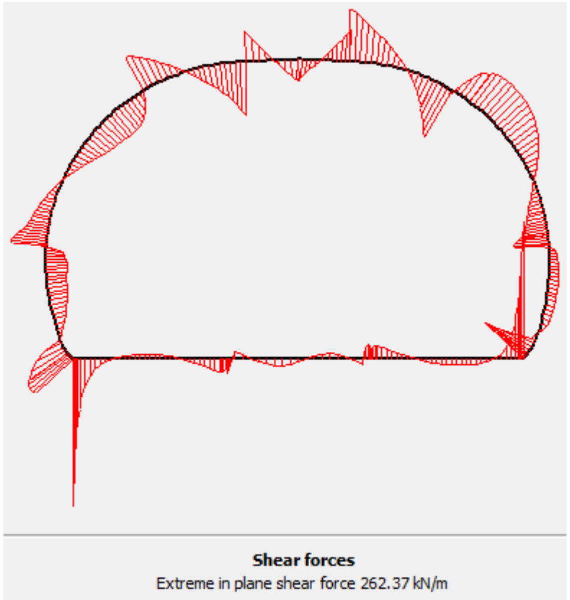

Figure 4-10 Shear Forces Diagram - Modeling of Final Lining Structure Based on Initial Geotechnical Investigation

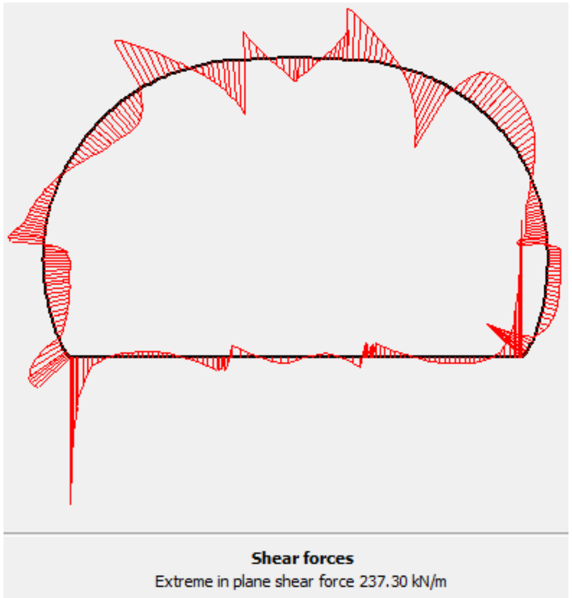

Figure 4-11 Shear Forces Diagram – Back Analysis by Modeling of Final Lining Structure Based on Ground Monitoring

The results show that the maximum shear forces base on the data from initial geotechnical investigation is about 10% greater than the values obtained from the back analysis models based on the actual monitoring deformation measurements (i.e., 262.37 kN, 237.30 kN).

4.5.2 Cost Estimation of Final Lining Design

Design of final lining reinforcement is based on the load-moment interaction curve. Thickness of 50 *cm* was selected for lining as shown in Figure 4-12 for this analysis. In the drawing of the interaction curve of the final lining, the strength of concrete was assumed 35 MPa and the concrete cover at 7.5 cm was considered (based on ACI 318-14 Code).

It should be noted that the tunnel was *"Type 1"* based on AASHTO T2-1991 Since the output of the numerical modelling is based on loads without coefficients. The loads have been multiplied by coefficients 1.3 and 1.6 for maximum load according to the ACI 318-14 Code.

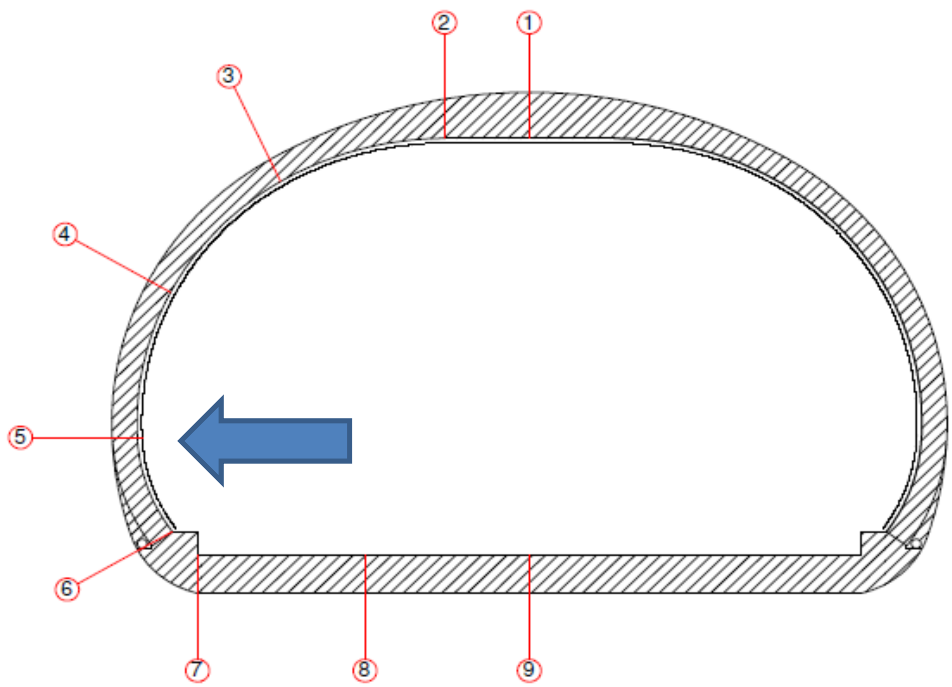

Figure 4-12 Tunnel Cross Section

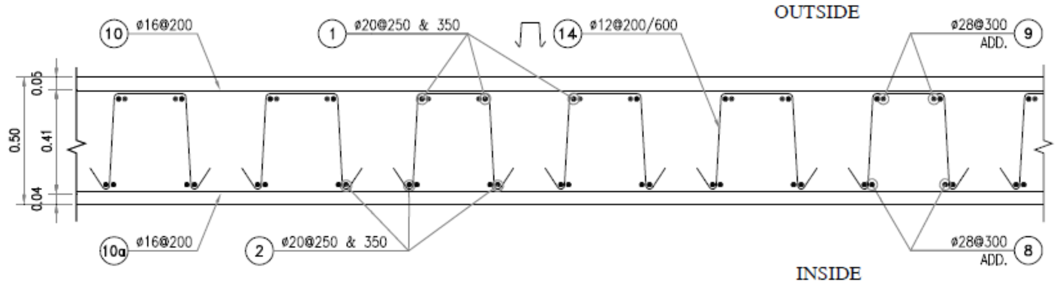

Figure 4-13 As-Built Lining Section According to the Original Design

As demonstrated in the as-built section (Figure 4-13), according to traverse reinforcement, the rebar is ϕ20@250 & 350 or on average in the form of ϕ20@ 300 and an extra rebar is also ϕ28@300. In the following, the force generated by the new modeling is shown in the interaction diagram that is based on the cross section of Figure 4-14.

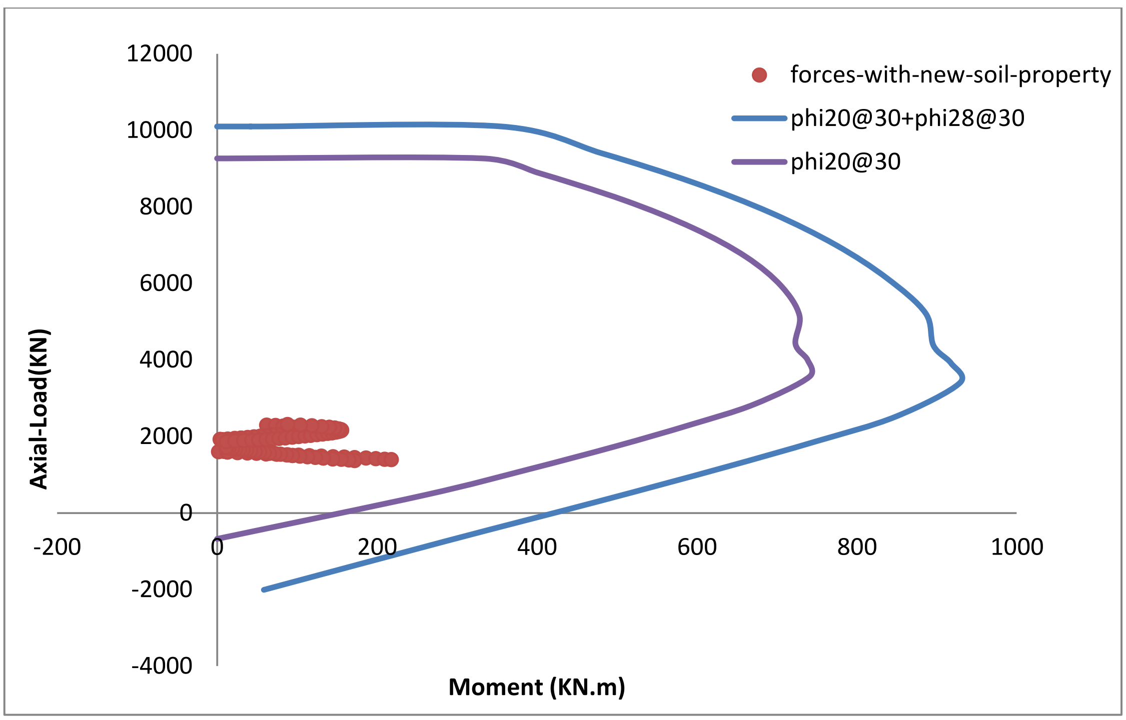

Figure 4-14 The Interaction Diagram Based on the Forces in the Initial and New Model

According to Figure 4-14, the relation between rebar strength and its load capacity is not linear, since the results of numerical modelling should be inside the graph to show the capacity of the final lining structure in the tolerance of loads. It can be concluded that in the case of using a new model, the use of longitudinal reinforcement without adding extra rebars is sufficient for the section under consideration. Calculation of added cost due to extra rebar are presented in the following section.

Calculation of Extra Rebar

To determine amount of an added rebar for a whole tunnel length the calculation is:

Extra Rebar*:* $\phi 28@300$

A_s *(*ϕ*28)* = 6.16 cm^2

By calculating the number of extra rebars in the cross section of the tunnel (Figure 4-13), a total of 24 extra rebars were determined as placed in the final lining structure. The total tunnel-lining perimeter is about 42 m. This project consists of two tunnels.

The volume of a rebar in a 1 m length of tunnel is:

Area of two layers of extra rebars in one section = (42/0.3) *2* 6.16 = 1,724.8 cm^2

Area of extra rebar in cross section of twin tunnel = 1,724.8 cm^2 * 2 = 3,449.6 cm^2

Total v olume in 1m tunnel length = 0.34496 m^3

Total weight of extra rebar in 1m tunnel length = 0.34496 m^3 *7850 kg/m^3 = 2,707.939 kg

Total weight of extra rebar along tunnels = 2,707.939 kg/m * 1080 m * 2 = 5,849,142 kg

According to the price of the steel on that time with labor cost per kilogram, which is provided in contractor's invoices as *$1.05/kg*, the total cost of a just added rebar is:

5,849,142 kg * *$1.05/kg* = $6,141,599.

Comparing the total cost of about %105 M, it is about 6 % of project cost. If a more detailed analysis of cost, saving is conducted, which could include lowering the lining thickness, reducing the initial supporting system (i.e., shotcrete …), and if other geotechnical parameters were also back analyzed, the total cost saving would be more.

This shows that if sufficient and an accurate geotechnical investigation is conducted before the contract based on GBR, the bid price could be at least 6% lower based on the extra rebar. Obviously, by performing geotechnical investigation in the early stage of each project, the owner can save on the cost of project based on a more accurate lower bid price.

4.6 Discussion of the Results

According to provided data and geotechnical investigation analysis of the case study project based on GBR and continued by assessing challenging factors in the Hakim Tunnel project, the following results can be expected:

- Based on lack of sufficient and accurate geotechnical information before contract, to reduce the risk, contractor overestimated the bid price.
- Based on contractor's invoices on geotechnical investigation, 77% of geotechnical investigation was done after contract.
- The results of monitoring showed that the actual deformation values were much lower than the initial estimated values. Thus, using optimal design, construction would have cost less.
- The results showed that Hakim Tunnel's design was somehow overdesigned.
- The bid price was based on the overdesign estimation of the project cost.
- Three challenging factors in the Hakim Tunnel caused overestimation.
- Analysis of the design, construction and bid price items showed that overestimation is due to assumption of low values of modulus of deformability (Es), which is about 5% -10%.
- Results show if overall sufficient geotechnical investigation (based on GBR) were available before contract, the total bid price could have been lowered by at least 6% on the extra rebar and overall about 10% lower.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS FOR FUTURE REASERCH

5.1 Introduction

Each project has its own unique features. In any underground project, geology and geotechnical characteristics are the main features of the site. If ground conditions are not well determined, the risk of the tunnel project increases. Therefore, the ground condition should be investigated and geotechnical parameters should be evaluated in the early stage of any tunnel project. Therefore, it is better to have these data gathered, determined, and a Geotechnical Baseline Report prepared and included in the contract documents. Based on these data, the important factors, which could increase the geotechnical risk challenge of the project, must be recognized and determined before the contract to prevent cost of overdesigning and unforeseen conditions

5.2 Research Limitations

Before starting any research study, it is essential to have a better understanding of the methodology and data collection to attain more accurate and reliable results from the data. This research was faced with different constraints that are defined as follows:

- Limitation in number of projects as a case study,
- Lack of accessibility to appropriate data for different parameters,
- Bureaucratic policy constraints in some organizations for getting required data,
- Accuracy of data from experimental and instrumentation monitoring.

5.3 Conclusions

Conclusions of this research are summarized as follow:

- Comprehensive geotechnical investigation should be done before contract by owner base on GBR,
- Complete geotechnical investigation based on GBR before contracts will decrease risks for owner and share project risks with contractor side,
- If accurate geotechnical parameters are not determined before the contract, the project cost and owner’s risk will increase,

- Overall and complete geotechnical investigation can reduce the total cost of project significantly by preventing conservative design,
- Geotechnical study based on GBR ca also help owners and contractors to have a better overview of uncertainty and risk challenges,

Therefore, geotechnical information in tunnel projects are vital. To properly design and construct any underground project, having a complete and suitable GDR and GBR in bid documents is very crucial.

5.4 Recommendation for Future Research

Recommendation for future research can be summarized as below:

- Extend the study to long tunnels and compare it with different methods of construction,
- Investigate geotechnical aspects of different type of contract regulation based on GBR such as the TBM method of tunneling,
- Use other factors of soil parameters for calculating efficiency of tunneling design,
- Study the projects (case studies) that ended up with legal disputes and analyze the possibility of dispute elimination if GBR had been available in contract documents,
- Study and investigate several similar projects to gain more accurate and reliable data for understanding what type of geotechnical aspects are more important and problematic in industry,
- Compare different types of contract-based GBRs in other underground infrastructures such as pipelines, chambers, sheeting and deep foundations.

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Biographical Information

Mohammad Haadi Sadaghiani obtained his Bachelor of Science in Civil Engineering from Sharif University of Technology, Iran, which is the most prestigious technical university in Iran. He started working in industry during his last year of school as a part-time junior engineer for SAZBON Consulting Engineering Co. After graduation, he joined a seven-line Tehran metro project as a project control and site engineer which was one of the biggest urban tunneling project in the country with a total project cost of about $1.2 Billion.

After gaining some professional experience in industry, especially underground infrastructure, he decided to pursue his higher education in construction engineering, and began his studies for Master of Science in Civil Engineering with a focus in Construction Engineering and Management at the University of Texas at Arlington. He graduated in May 2018. During his graduate study, he studied trenchless technology, which is another sector of underground infrastructure, to help him gain valuable knowledge in this industry.

Haadi’s future plans include getting more involved with different sectors of construction and obtaining the valuable experience needed to build a network with experts and professionals.