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Engineering characteristics of rocks in Qatar; Applications on excavation and tunneling

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The American University in Cairo

The School of Sciences and Engineering

Engineering Characteristics of Rocks in Qatar; Applications on Excavation and Tunneling

A thesis submitted to

The Department of Construction Engineering

In partial fulfillment of the requirements for the degree of

Master of Science in Construction Engineering

By

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Abstract

Excavation as well as tunneling have become fundamental operations in the advanced civil engineering field. In Qatar, many subsurface construction operations take place in rocks. However, the lack of studies and research that analyze the subsurface rock components from a geotechnical engineering perspective has created unexpected construction conditions. Most of similar studies handled concerns about properties related to oil and gas fields.

This research aims to provide a geotechnical study for rocks in Qatar, and to illustrate the impact of the existence of these rock layers on two civil applications; namely excavation and tunneling. During this study, soil investigation reports and rock samples are collected from several bores located in Qatar, and a classification system is utilized to classify the rock samples to identify and study the properties of the existed rocks. Also, numerous production rates from different tunneling and excavation projects are recorded and analyzed, in order to clarify the relation between these rates and the classified rock layers.

Based on this analysis, a geotechnical study and mapping system for the rocks in Qatar are presented. Reliable tools for predicting the average productivities of excavation and tunneling projects in Qatar are developed, these tools are aiming to facilitate designing, bidding and executing processes involved with these types of rocks.

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Chapter One: Introduction

1.1   Problem Statement

Qatar, the developing state is situated on the southern shores of the Arabian Gulf, has - over the last two decades - experienced unprecedented construction and infrastructure boom, including the design and construction of new cities, towers, and mega projects, which requires good knowledge of all the related aspects that may affect the success of these projects. As mentioned in the Qatar Vision 2030, Qatar has several challenges regarding the control of the proposed development, and one of these challenges is managing growth and uncontrolled expansion, which can be controlled by knowledge, implementation, researches and studies in the construction and urban fields. Consequently, the need of advanced studies on its natural resources and conditions have been raised during the last decade in order to address the necessary sustainable usage and identify problems of these resources for reaching the expected economic and efficient growth in the short coming years.

These necessary studies require detailed geotechnical engineering reports. Geotechnical engineering is an important field of engineering which deals with the behavior of earth materials. More precisely, geotechnical engineering identifies the behavior of soil and rocks under the influence of loading and construction forces. Its findings are used extensively in many engineering applications; among which temporary and permanent excavation and tunneling. Geotechnical studies run field and laboratory investigations for determining the underlying engineering properties of the soils and geomaterials on sites which are subsequently used in the engineering analysis, design and construction.

Rocks are considered one of the main formations in Qatar forming the major shallow geotechnical component across the state. Generally, much of Qatar's offshore "earthly" deposits (soil and rock) are comprised of calcareous sands, silts, and clays, overlying diagenetic limestones interbedded with dolomites, marl, shale and hardened clays, as noted by Akili (2004).

This situation introduces many challenges in the construction process in Qatar, and this is admitted by all the geotechnical engineers who have worked in this area; experiencing many difficulties in construction. This situation necessitates adapting the commonly used classification methods in rock mechanics to the specific rock requirements, especially in Qatar. Since the

planning of future constructions relies mostly on past knowledge of similar areas or on rocks studies of similar features, this research intents to fill the gap between region's geological data and its engineering analysis and methodology.

Literature survey indicates that numerous studies and research related to the rocks in Qatar were geared to satisfy the needs for determining the Qatari rocks' features for Oil and Gas exploration purposes. However, several geotechnical engineering parameters were ignored.

In fact, the lack of studies covering and analyzing the specific rock properties and characteristics of Qatar from a geotechnical engineering perspective has encouraged the author to make an attempt to try to fill this gap. This was accomplished by combining all the obtained soil/rock investigations results with practical construction applications, which will eventually contribute to the country's development vision.

1.2   Qatar Geology

1.2.1   General

In order to follow a rational sequence in the conducted research it is crucial to study first the geology and topography of the state of Qatar. Qatar is located in the Arabian Peninsula of the Arabian plate which consists of two main tectonic units; the Arabian Platform and the Arabian Shield which is an isolated craton formed of a complex igneous and metamorphic rocks. Even though Qatar is located in the stable shelf of the Arabian Plate, the Arabian shield has exerted a great influence on the geological history of the formation of Qatar's soil map.

Qatar's exact location on the Arabian shelf is in the broader zone of the interior platform, which forms part of a regional NNE-SSW trending high (the Qatar-South Fars Arch).

On the eastern side of the Arabian Shelf- where Qatar is located- sediments expanding for 14km were formed, due to the existence of deepening basin during most of the Phanerozoic.

While checking Qatar's Soil map it is clear that in the northern Qatari lands, the Zagros Fold Belt is bounding Qatar, where major parts of Qatar are formed by a very wide N-S elliptical anticline which leads to the exposure of the Middle Eocene upper Dammam formation.

In the western Qatari lands, similar tighter NNW-SSE trending folds are formed due to the Dukhan anticline and Zekrit and Salwa synclines. Due to the existence of the Dukhan anticline, the lower older Rus and Dammam formations were exposed to the surface. In the 80km long and 4.5km width north domal structure, a 50km oil productive formation can be found. In certain regions in the southern extension of Dukhan anticline, wind erosion surviving mesas appear on its both sides covering its flanks. These mesas are considered the only elevated topographical feature found in the southern and south western regions of the peninsula of Qatar and are younger tertiary sedimentation that belong to the Hofuf formations and the Miocene and Pliocene Dam. These mesas are composed of carbonate, marl, clay and gypsiferous rocks originated from the Dam formations and are covered by agglomerates and clastic materials originated from the Hofuf formations, composing the comparatively thick layers of the Hofuf and Dam formations, which are located from the Salwa Gulf until the east cost of the Saudi Arabian's lands, as shown in Figure 1.
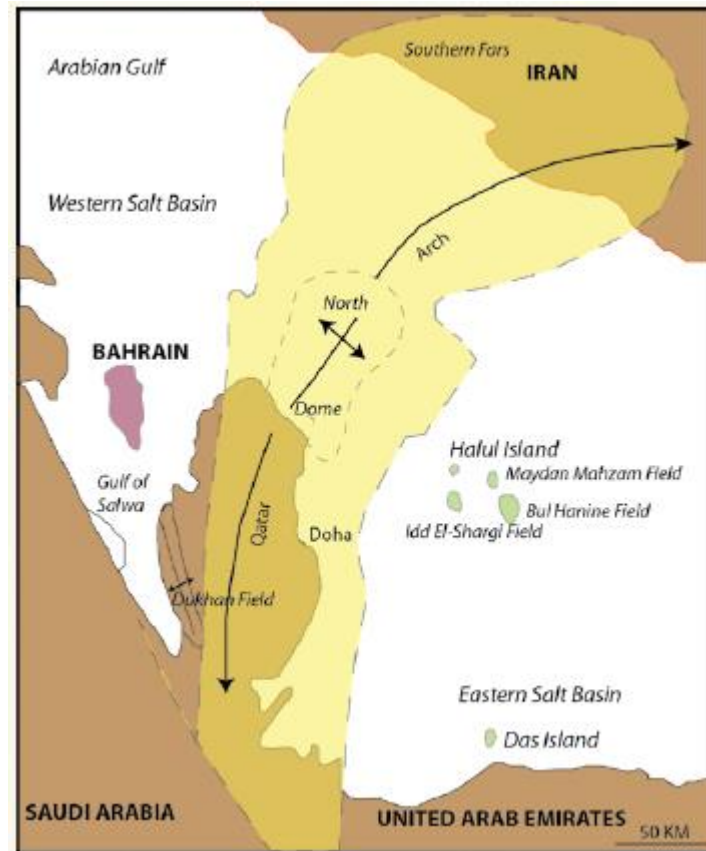
Figure 1: Structural configurations of the rocks in Qatar
(http://www.qu.edu.qa/offices/research/esc/)

Qatar's area is around 11610km^2 forming a peninsula in the Arabian Gulf. The Shamal wind shaped a deflation surface for topography of the country apart from few low hills in the North West regions on the peninsula. Qatar's surface topography ranges between 6m below sea level in some regions like Dukhan sabkha and up to 103 m above sea level in the southwest regions, yet the vast majority of the landscape is around 40m above sea level.

Qatar's geological formation mainly consists of uniform limestone beds covered in some locations with younger starta which form the mesa-type hills. In around 8% of Qatar's surface, Lower Eocene Rus Formation exists, which contains dolomite and limestone with some Miocene outcrops.

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The physiographic features of Qatar were classified in many studies; but the most comprehensive and detailed one was performed by Ashour 1987. In Ashour 1987 classification, Qatar's physiographic features were divided into eight groups as following:

- Sand accumulation (Nebkhas, Sand dunes and Sand sheets) (Figure 2),

- Duricrusts,

- Costal sediments (Subtidal zone and Intertidal flats) (Figure 3),

- Dohool (Krast features) (Figure 4),

- Sabkhas (Dukhan Sabkha and Umm Saied Sabkha) (Figure 5),

- Fluvial sediments,

- Hamada Plain sediments, and

- Depression soil (Rauda).

Figure 2: Sand accumulation in Qatar (http://www.qu.edu.qa/offices/research/esc/).

Figure 3- Costal Sediment in Qatar (http://www.qu.edu.qa/offices/research/esc/).

Figure 4 - Dohool (Karst features) in Qatar (https://wahyuinqatar.com/2009/06/16/musfer-sinkhole-karst-cave/).

Figure 5 - Sabkhas in Qatar (http://www.qu.edu.qa/offices/research/esc/).

1.2.2 Surface Geology

Qatar has a unique surface geology since it is overlaid by two contrasting lithological regimes which are: (Figure 6)

- Carbonates sediments which form the majority of the surface geology,

- Clastics Materials which form Miocene, Pliocene and Pleistocene starta.

The seabed geology exposed formations in Qatar that can be summarized as follows:

- Hofuf Formation (Late Miocene-Pleistocene): this formation is named after the Saudi Arabia's village and represents around 3% of the exposed rocks in Qatar and is the youngest Neogene deposits in the country. It is composed of three different faces, namely the clast-supported conglomerate, the coarse-grained sandstone and the fine-grained sandstone.

- Dam Formation (Miocene): this formation is named after a mountain in Saudi Arabia called Al-Lidam with its lower section being cropped out. This formation is divided in Qatar in two sub-formations which are:

  - The Lower Dam sub-formation, which is composed of about 30m white and light grey fossiliferous limestone, marls and clays with marine origin

  - Upper Dam sub-formation.

- Dammam Formation (Lower-Middle Eocene): this formation is named after the city in Saudi Arabia. This formation is divided into two sub-formations in Qatar as follows:

  - Upper sub-formation, with the most popular terminology used to classify it being the Umm Bab or Simsima member, and overlays the majority of the surface of Qatar. It is comprised of neomorphosed chalky limestones and is locally dolomitized or silicified. The Abaruq member is the only region locally distributed and found in the lower areas between the boarders of Zekrit area and Dukhan anticline and it consists of silicified dolomite and dolomitic marly limestones.

- Lower sub-formation also known as the Midra Shale member, which consists of gypsiferous shale with shark teeth, and the Dukhan member which consists of large- foraminifera bearing limestone.

- Rus Formation (Lower Eocene): this formation is named after the eastern province of Saudi Arabia. The upper part of this formation is the only part expanding through Qatar for about 1km from the Qatar Petroleum plants in the Dukhan. The Fhahil's area formation is exposed for about 25m. The upper formation is classified in two members as follows:

  - Al Khor member, which is composed of about 25m of fine-grained chalky limestone, overlaid with clay and marl.

  - Traina member, with its upper part being comprised of coarse limestone and mud balls and its lower part consisting of alterations of marls and dolomitic limestone.

Period	Epoch	Sub-formation	Member	Approximate Thickness (m)	Lithology
Quaternary	Holocene	-	-	-	Mobile sands and bioclastic beach sands.
	Pleistocene	-	-	-	Fixed dune sands, sabkha deposits and cemented beach rocks ('caprock').
	Lower Miocene	Lower Dam	-	0 – 30	Fossilliferous marls, clays and thin limestone. Occasional green and red clay bands.
Tertiary	Middle Eocene	Upper Dammam	Abarug Limestone	Eroded	-
			Abarug Marl	Eroded	-
			Simsima Limestone and dolomite (also known as Umm Bab formation) (WSL, SL, BSL)	Up to 30	Buff to pale-brown chalky limestone with siltstone inclusions.
		Lower Dammam	Alveolina Limestone	0 – 1	-
			Midra Shale	0 – 10	Yellow-brown laminated shale, fossilliferous with limonite and phosphate nodules.
			Fahahil Velates Limestone	0 – 1	-
	Lower Eocene	Rus	Khor Limestone	0 – 1	Buff to grey-brown massive, pitted, vesicular, dolomitic limestone.
			Undifferentiated Carbonate Facies (RUS)	Up to 20	Cyclic deposition of weak carbonate marls, siltstones and thin limestone.
			Undifferentiated Sulphate Facies (RUSGYP)	Up to 100	Thick deposits of anhydrite and gypsum with marl and thin limestone.

Figure 6 - Lithological regime existed in Qatar.

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1.3   Objectives of the Research

The objective of this research is to provide useful understanding of the Qatar's geology in order to develop a geotechnical rock classification system and to relate this understanding and analysis to two main civil engineering techniques; namely the excavation and tunneling techniques. More precisely, this study aims to assist geotechnical engineers in their top priority tasks such as the recognition of rocks properties and their engineering properties, the identification of the most appropriate design and construction method together with cost effectiveness, durability, and safety.

1.4   Research Approach and Scope of Work

1.4.1   Research Approach

Qualitative and quantitative research approaches are employed in this research. It follows the quantitative research for issues such as sampling, data collection, and data analysis, while following qualitative methodologies in some extend for its outcomes and the data analysis.

Rock samples as well as soil investigation reports were collected from 38 different locations across Qatar, in order to study the rock properties existed at these locations, and to be capable of classifying the studied rock layers properly using the Rock Mass Rating (RMR) classification system. In addition, 36 tunneling projects and 22 excavation sites were visited. These projects have taken place at the locations where their rock layers have studied and classified by the author. As a result, correlations between the rock layers qualities and the corresponding production rates recorded in these projects were studied and analyzed, and prediction tools for obtaining the average productivities based on the RMR classification rock grades were developed.

In addition, this research highlights the importance of geotechnical investigations' which establish the first step in applying scientific methods and engineering principles for obtaining solutions in the civil engineering problems that engineers may face during their work in Qatar.

1.4.2 Scope of Work

The scope of this research focuses on the geotechnical characteristics of the rock layers existed in the state of Qatar, and the classification of these rocks using Rock Mass Rating (RMR) classification system, that will be utilized throughout the research study. This classification system involves several geotechnical parameters on the rating process, such as: compressive strength, rock designation quality (RQD%), weathering and joints state, and groundwater conditions. In addition, two fundamental civil applications will be highlighted in this research, namely tunneling and excavation, in order to illustrate the impact of these rock layers existence on these two civil operations.

Chapter Two: Literature Review

2.1   Current Construction Challenges

Over the last two decades the State of Qatar, situated on the southern shores of the Arabian Gulf, is experiencing an unprecedented offshore construction booming, including the design and construction of new cities, towers, railway lines and stations, and oil and gas platforms to facilitate their production and transport.

However, rocks in Qatar present many challenges in engineering terms, since all involved engineers experience many difficulties. Thus great effort is given to adapt commonly used classification methods of rock mechanics, as past knowledge of rock areas with similar features is very crucial for such engineering projects. As a result, needs for expressive geotechnical studies of the existed rocks have raised, in order to ease the process of designing, bidding and executing the current and future projects.

2.2   Geology of Qatar

Obviously, the first necessary step for such studies is the complete understanding of Qatar's geology in order to properly classify the existed rocks and obtain the correct goals of such a research. This section presents a brief literature study on Qatar's geology.

2.2.1   Description

Most of Qatar's marine soil deposits consist of diagenetic limestone interbedded with dolomites, marl, shale and hardened clay covered with calcareous sands, silt and clay. Qatar region, located in the Arabian Peninsula overlooking the Arabian Gulf, is undergoing an increasing development process in construction projects such as buildings, industrial plants, mega-project infrastructures, highways, and underground subways. Most of Qatar's earth deposits consist of thin unconsolidated desert soil covering calcareous limestone apart from coastal margins where soil consists of extensive saline soils (Sabkha) (Akili and Torrance, 1981).

Due to Qatar's location, its soil geological information follows the well detailed and defined stratigraphy of eastern Saudi Arabia, obtained mainly from past oil, gas and water exploration projects (Powers et al., 1966), reflecting the importance of advanced geotechnical studies for itsrocks, from a civil engineering perspective.
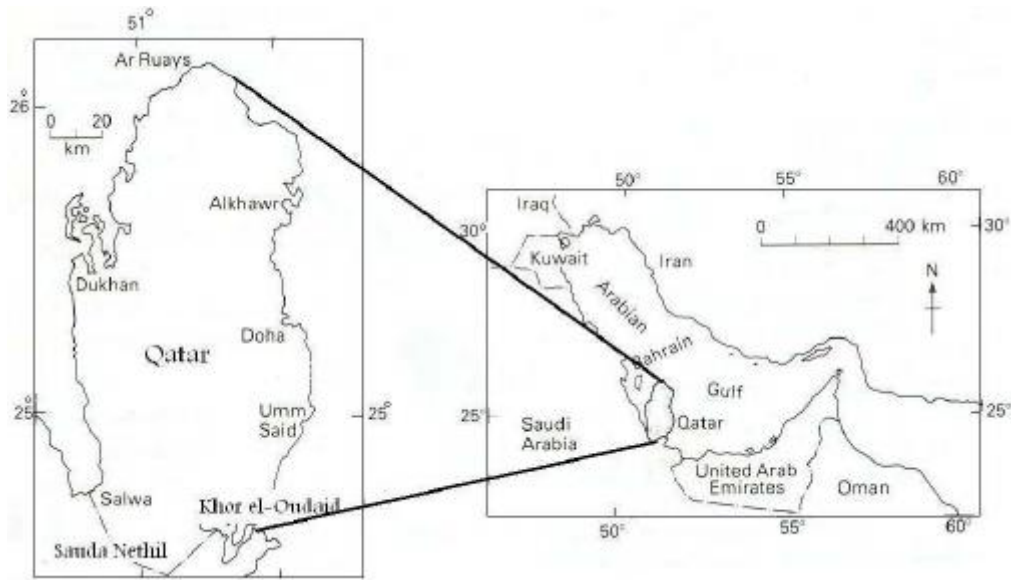
Figure 7 - Qatar location map (Ashour et al., 1991).

However, Qatar's topography is known to be subdued, and its soil is mainly composed of Tertiary limestone and dolomite rocks immersed with shale, clay, marl and gypsum. In some regions, rock formations are also covered with Quaternary deposits(CAVALIER, 1970).In a structural geology perspective, Qatar is located on the tip of an elliptical shaped anticline dome arch with itsmain axis stretching from North to South into the Arabian Gulf as shown in figure 7. Erosion and uplift are present in this anticline area, exposing the oldest Rus formation rocks along the anticline major axis. The main details of Qatar's topography and landscape are listed below:

- Qatar's location is centered at 25°N., 51°E., exposed between the Arabian Shield and the mobile belt of Iran.

- The net area of Qatar is about 11610 km^2 and stands out in the Arabian Gulf forming an eastern appendix (Figure 7).

- Qatar's landscape is considered as low-relief with a maximum elevation of ~110 m msl.

- Its main axis is orientated north-south with an elliptical anticlinal arch (Figure 1).

- Qatar's geology formation consists of Tertiary limestone, which started with a marine transgression in the Paleocene, and of dolomite interbedded with gypsum, clay, marl and shale. Certain regions are covered with Quaternary deposits (CAVALIER, 1970).

- Qatar's climate is dry arid with its past climate during Miocene and Pleistocene, being more moist and dry (Butzer, 1961, Ibrahim et al., 2002).

Until the end of Eocene epoch, Sabkha's shallow-marine conditions were present with a carbonate-evaporite sequence (Rus and Dammam formations) being present as well. A widespread of unconformity appeared at the end of the Eocene due to the sea regression which caused the absence of Oligocene deposits. At 25° 20' south latitude, depressions and sinkholes are present along with northern deep gypsum and anhydrite horizons from the Eocene era(CAVALIER, 1970).Moreover, during the Miocene epoch, the Upper Dammam unit limestone was crafted forming pathways for underground water tables.

However, Qatar's current underground water is contained in Tertiary sedimentary rocks comprising the main aquifers. They are exploited at comparatively high rates and are recharged from occasional rainwater that flows from the same north and east rocks through Saudi Arabia in the direction of the regional dip.
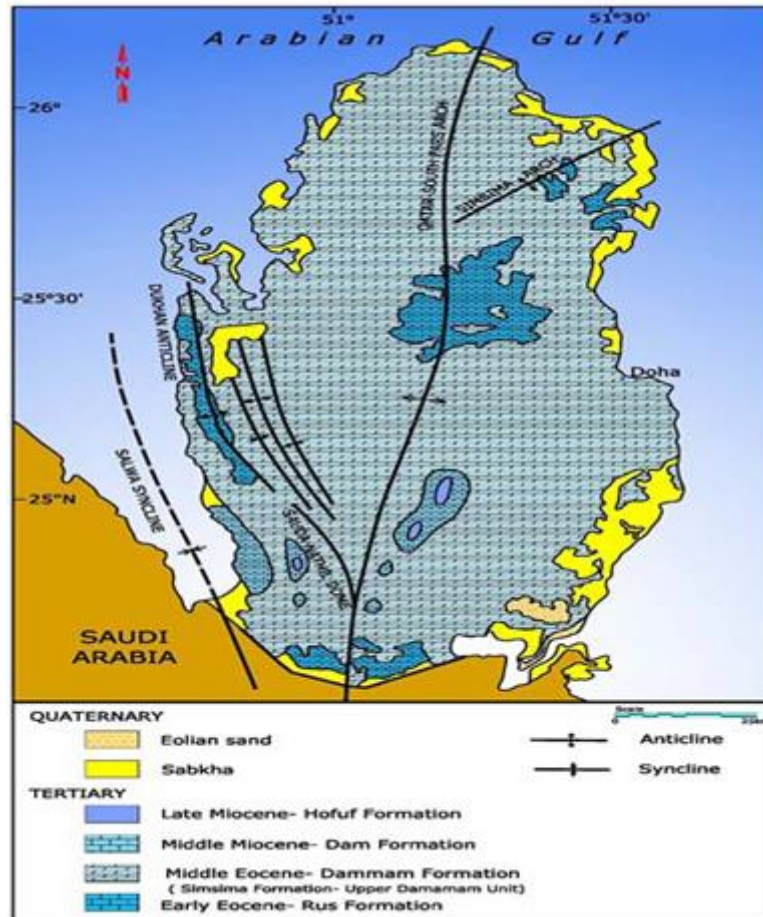
Figure 8 - Simplified Geological Map Showing the Main Structural Elements of the Qatar Peninsula (Modified after Cavalier, 1970).

Generally, Qatar's exposed rocks consists of the following formations(Embabi and Ali, 1990) (Figure 8):

a. LOWER EOCENE RUS FORMATION: With thickness between 42 and 112m this formation consists of Soft, Dolomitic, and Chalky limestones, Gypsum, Anhydrite, and Shale.

It was proved that the dissolution of this anhydrite and gypsum formation caused the most depressions which resulted in a large number of surface collapse depressions (Embabi and Ali, 1990).

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b. LOWER-MIDDLE EOCENE DAMMAM FORMATION: Expanding across the surface of Qatar and overlying the Rus formation. This formation presents a thickness between 30 to 50m and is comprised of 2 units:

- The Lower Dammam Unit: Originated from the fhiheil limestone member, Midra shale member, and Dukhan limestone member.

- The Upper Dammam Unit: Where all Qatar's sinkholes are present, originated from the Simsima limestone, dolomite member, Abarug dolomite member, and marl member.

c. LOWER-MIDDLE MIOCENE DAM FORMATION: With a thickness of about 80m, and characterized by sea and continental erosion regression this formation consists of:

- Shallow marine deposits.

- Lacustrine deposits.

d. UPPER MIOCENE TO PLIOCENE HOFUF FORMATION: This formation's origin comes from the Arabian shield and the Arabian Shelf transferred by the large river system with a thickness of about 18m.This formation consists of:

- Fluvial sediments.

- Coarse sand and sandstone with pebbles of various rocks(Ibrahim et al., 2002).

e. QUATERNARY: A shallow marine and continental sediment consisting of:

- Sabkha deposits,

- Sand dunes,

- Calcareous Sand.

Qatar's bedrock mainly consists of early to late Tertiary and young limestones embedded with dolomites, marls shales and clay. Underneath, limestones belonging to the Eocene era are

present. This limestone is considered a "Simsima" Member of Upper Dammam Sub-formation being approximately 45-55 million years old (CAVALIER, 1970). Simsima limestone's main characteristics are shallow water carbonate limestone with layers and lenses of silt and pre-evaporate formations of anhydrite and gypsum. An overview of Qatar's geological structure features is presented below based on previous works:

1. **Rus Formation:** This formation consists of Soft, Dolomite, and Chalky limestones, Gypsum, Anhydrite, and up to a 100 m thick layer of shale. This type of formation undergoes multiple surface-collapse depressions due to the dissolution of anhydrite and gypsum (Embabi and Ali, 1990). Rus formation is considered to be the oldest exposed rock in Qatar peninsula. It is exposed specifically near crests of anticlines. Generally, Rus formation overlies the unexposed Umm Erradhuma formation of Palaeocene-Lower Eocene age (Smout, 1954). (El-Sayed)stated that Rus formation is overlain, in a conformable way, by the Dammam formation which constitutes the most widespread outcrops of Qatar. The Rus Formation is one of the main charged aquifers of the Qatar peninsula and one of the main of the Arabian Gulf states.

2. **Dammam Formation:** Covering most of the Qatari peninsula and overlying the Rus formation is comprised of two units:

- Upper Dammam Unit.

In this unit, most of the Qatar's Sinkholes appear and is mainly composed of the Simsima limestone, of 30m thickness on average covering also the most soil surface, and Dolomite member with some eroded Abarug Dolomite and Marl members. The Simsima limestone is described as fine to medium grained, poorly bedded, chalky crystalline calcareous limestone and dolomitic limestone with various sizes and irregular weaker siltstone filled joints with occasional attapulgitic clay thin layers (CAVALIER, 1970).

- Lower Dammam Unit: It is composed of two limestone members with the Midra Shale member in between.

3. Dam Formation: The Miocene was characterized by sea regression and continental erosion. This formation consists of a more than 30m thick shallow low marine and lacustrine deposits mainly from fossili ferrous marls, limestone, and clays.

4. Quaternary Deposits: Referred also as shallow marine and continental precipitates and sediments, this deposit consists of:

- Sabkha deposits. These coastal salty deposits are located on the coastline, with their formation being related to the phenomenon of capillary moisture movement, since this process takes place between the shallow water table and the evaporation mechanism leading to an ongoing salt precipitation dissolved in the ground water.

- Aeolian sand dunes.

- Calcareous sands where their surface deposits are related to the wind moved materials during high wind periods.

5. Karstification: Concentrated within the gypsum, dolomite, anhydrite and limestone horizons of the Eocene Rus and Dammam formation, appears in many regions of the Arabian Gulf including Qatar. This formation appears in depressions, sinkholes, caves and solution hollows and found in two main Qatar locations:

- The first location is Central Qatar and realized due to the extensive subsurface dissolution of carbonate and sulfate deposits under the middle Pleistocene wet climate and consequent subsidence.

- The second location is Northern Qatar and is referred as pitted krast Terrain, due to the joint flow drainage which led to differential dissolution forming this deposit.

In another study, (Sayed and A.) focused on the rock samples that represent the upper part of Rus formation and four different region samples were collected. As mentioned above, Rus formation is considered as one of the main aquifers of the Arabian Gulf region including Qatar. Thus, precise monitoring and description of the aquifers are highly needed for conducting efficient and

effective water producing formation management. The water recovery and distribution parameters are:

- Porosity,

- Permeability,

- Hydraulic conductivity, and

- Effective thickness.

The goal of this study was to establish a comprehensive interrelationship that will define the most significant factors affecting the Rus formation flow and storage properties. Numerous observations on the Rus formation properties originated from this study such as**:**

1. Rock porosity and permeability values vary significantly.

2. Reliable regression equations have been determined relating the rock's pore volume (V p) to the permeability per rock porosity (k *I* Jl) ratio.

3. The porosity-permeability relation is affected by the semectite pore filling and the dolomite pore lining along with certain mineral grain dissolution.

2.2.2 Shaliness Factor

Shaliness factor (b) defines the clay content in argillaceous rocks(Hill): and is calculated for limestone samples of the Rus Formation by the use of the following equation (Hill and Millburn,1956):

$$Fa = F_{lim} (100 \, Rw)^{\,b \log (100 \, Rw)} \qquad \text{Equation (1)}$$

Where Fa isthe apparent formation factor.

After extensive study of the Rus formation, authors concluded to the following conclusions (El-Sayed, 1987):

1. Reliable formation factor-porosity relations were obtained.

2. Limestone samples of Rus Formation can be distinguished by a characteristic value of shaliness (b) in each study area.

3. The studied samples were entirely water-wet, thus, estimated petrophysical parameters may also be used for water reserve estimation.

In Qatar, the close-to-surface limestone soil is unique in its lithological composition since it has undergone many diagenetic changes after its deposition. One example is the combination of limestones with clayey matrix material. This combination is a mixture of rock fragments with secondary fraction. While mostly the matrix material is clayey, it could be sometimes cemented with gypsum, anhydrite or calcite grains. Due to these compositions, soil classification is challenging since these materials present the following characteristics:

- Inability to collect samples of the material in its primary state.

- Variation in composition and properties.

- Prone to degradation especially when encountering water.

In Qatar, Sabkhas,also known as "Sabkhah" or "Sabkhat", represents a unique geomorphological feature covering around the 7% of Qatari land surfaces (Ashour et al., 1991). According to (Ashour et al.), Sabkhas in Qatar are typically flat containing shallow water table areas. Water from these areas is highly saline and is either directly connected to sea or ground continental water. Other sources that contribute to the partial recharge of such systems are the tidal floods, rainfalls and surface runoffs. The most common subsurface sediments are evaporites, quartz grains and mud, sodium chloride, classified into three types:

- The first type is inland sabkhas, which is considered more mature than the second type.

- The second type is coastal sabkhas, which is called supratidal flats and represents a larger percentage in Qatar.

- Anthropogenic sabkhas, which is less known than the other two types, and found in the inhabited areas and cultivated depressions.

In Qatar, Sabkhas were originally formed and elevated due to some circumstances such as (Ashour et al., 1991):

- The flat topography and surface morphology of the peninsula.

- The shallow coastline and coasts of Qatar.

- The dry, arid and hot climate.

- Variations in the sea level.

- Water table.

- Geological setting.

- Anthropogenic interference.

In addition, (Thomas and Goudie) described Sabkha as a closed depression with a saline surface in arid environments, with flat saline region above the mean high tide level, but with an undergoing periodic inundation

Sabkha has been studied closely in several Arabian Gulf regional areas (PEHTHUISOT, 1977, Shinn, 1973, Evans, 1966, Evans et al., 1964, Evans and Bush, 1969, Kendall et al., 1998, Kirkham, 1997, Patterson and Kinsman, 1981, Wood and Wolfe, 1969). Sabkha has been studied also in broader works (Holm, 1960, Kassler, 1973, Goudie et al., 2000), yet Sabkha in Qatar was not carefully studied even though the fast growth and booming in construction activities increased the need for such detailed maps for providing detailed information about the landforms. Some efforts have been found in research projects funded by Qatar University for Qatar sand dune evaluations by Embabi and Ashour (1983, 1985) and Sabkhas study by Ashour et al.,(1991)with both projects being published exclusively in Arabic.

2.3   Characterization of rocks in Qatar

Qatar's topography is characterized by low elevation except for the North West region where some modest hills can be found. Qatar's exposed stratigraphic succession is formed from Tertiary limestones and dolomites ininterbeded clays, shales, and marls locally covered with Quaternary and recent deposits. Qatar's oldest exposed rocks belong to Rus formations from the Lower Eocene limestone, as previously mentioned. Furthermore, Qatar's land surface is generally covered by dolomites and limestones. Comprehensive studies have focused on the sedimentology, the primary structures, and the stratigraphy of the Eocene rocks in Qatar (CAVALIER, 1970, Purser, 1973, Abu-Zeid and Khalifa, 1983, Abu-Zeid and Boukhary, 1984, Hamam, 1984, Boukhary, 1985).

Since the Cambrian period, the Arabian Gulf basin accumulated evaporitic and carbonate sediments (CAVALIER, 1970). According to (Fourniadis, 2010), Qatar's seabed presents a sedimentary succession on its top with an estimated depth of over 10 km. Sabkha deposits and Quaternary marine cover the Stratigraphy beneath Doha and overlaying the Eocene Dammam and Rus formations. In the Upper Dammam formation, the Simsima limestone member protrudes more than 80% of the earth's surface in Qatar including Doha's surface. The Simsima limestone member has been the founding stratum mainly because of its thickness and geotechnical features in most developments of this region.

Furthermore, (Akili and Jackson) revealed in 1998 that in many budding sites in Qatar, diagenetic limestone was found composed of rock mass with matrix material of rock fragments and solid grains. The limestones were embedded with finer grains such as clays or minerals, like anhydrite, calcite, gypsum or other mineral mixtures. The prominent feature of this matrix material is its cemented structure that could be greatly affected by enforced loads and encountered moist. Working this matrix material can introduce several issues, due to its heterogeneity and un-unified composition. Thus, it hard to estimate the possible differential settlement, its decreased strength upon wetting and possible cemented structural collapses when undergoing different loading forces and water exposure.

To have a better overview of the rock layers in Doha, a geotechnical study was done by (Stypulkowski et al., 2014). During the shafts excavation in Abu Hamour area in Doha, authors have encountered two rock domains:

1- **Simsima Limestone**: comprise about 24.5m deep and contains Dolomite of upper Dammam formation, it is subdivided into Simsima A,B and C. Simsima C is at top with loosely compaction formation and contains a mix of boulders of dolomite (40%), carbonate and clay, with fine to coarse matrix. Colors differ from greenish grey, buff and light yellow with streaks of dark brown. No bedding structure is found, while gypsum lenses, vugs and cavities are existed. Simsima B is considered same composition as Simsima C, however, the strength is increasing with depth, since the grade of compaction becomes higher and the percentage of vugs and cavities decreased while the amount of gypsum lenses increased. Simsima A is chalky white, light yellow and greyish in color.

2- **Midra Shale**: is the base of Lower Dammam formation, located below Simsima A, as the transition from Simsima A to Midra shale is observed with 5-10 cm thick gypsum layer all around the shaft. Midra shale consists of shale/mudstone, claystone and limestone. It is found to be 8 m thick with chalky white, grey, pinkish, and greenish and moderate strong to very strong limestone despite the differences in strength for the limestone existed in this layer. Mudstone and claystone are found to be light to dark buff in color and not very similar in strength (moderate strong to very weak), grain sizes (most of it are coarse grained) and internal structure. Greenish clay in limestone was found while the percentage of clay generally in this band is about 50%.

Obviously, one of the most common layers that are found in Qatar is Simsima limestone. The Simsima limestone according to (Fourniadis, 2010) is an irregularly dolomitised, light grey to brown crystalline limestone, with local intercalations of chert and gray attapulgite (a type of swelling clay). Following its deposition in a shallow marine environment, sea levels dropped, exposing the rocks to weathering during the Oligocene. Wet climatic conditions during the Pleistocene initiated the development of karst dissolution' features of various sizes (from centimeters to tens of meters long) in the Simsima Limestone(Sadiq and Nasir, 2002). These karst features are often infilled by variably cemented fine-grained material.The Simsima limestone is the main layer of the soil formations and deposits in the Qatari capital, Doha. The Simsima limestone has a complex weathering pattern since some unweathered rocks sometimes overlay weathered rocks and it also have dissolution cavities infilled with uncemented materials. Most of the limestone in Qatar undergone a complex and intense diagenesis history which led to the existing mixture of:

- Hard re-crystalised original limestone.

- Diagenetically derived matrix materials referred to as "Secondary materials"- which varies from massive gypsum, carbonate siltstone and through to clay material.

The clays are classified as attapulgite formed from bands of silica tetrahedra and varies from palygorskite in the replacements of the structure (Grim, 1968).The limestone main component is mostly calcite well cemented yet sometimes is dolomitize, most of the limestone show great unconfined compressive strength ranging from 10 MPa to 100 MPa. The secondary material differs in degree of cementation and composition when the secondary material is subjected to water it shows characteristics of soft to firm clays (Akili and Jackson, 1998). The Simsima limestone- the predominant surface rock composition in Qatar and Eastern Saudi Arabia- has some distinctive characteristics which are (Akili and Jackson, 1998):

- The presence of large amounts of vugs,

- The presence of irregular joints mostly filled with weak materials such as siltstone,

- The occasional presence of thin layers of attapulgitic clays, and

- The occurrence of Chert bands especially noticeable near the base and the top of the soil.

These features lead to characterizing the Simsima limestone as anisotropic condition.

The major factor that affects the geotechnical properties of Simsima limestone in Qatar is the relative percentage of original limestone to secondary material, and the degree of cementation of it. For example, when the rock contains high percentage of weakly cemented secondary carbonate material, it means that rock mass generally will show lower strength and stiffness. An engineering group of the geological society (London) (Standard)BS 5930, (1999) has developed classification scheme in which different degrees of rock quality and weathering condition in the rock mass can be determined. According to this approach, two different materials are assumed to be the components of the rock mass, this approach can be applied in the case of the Simsima limestone, in which unaltered limestone contains different quantities of weaker carbonate and argillaceous matrix material. The percentage of rock and matrix material are estimated and used to classify the rock mass into rock quality zones. Knowing that other criteria such as core

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recovery, degree of cementation of infill material, and intact rock strength are being observed. The mentioned quality zones are representing an approximate engineering behavior. Table (1) shows the proportions of rock and matrix and the corresponding engineering behavior. As fresh to moderately weathered material is defined as "rock", and highly weathered material to residual soil is defined as "matrix".

Table 1 - Rock quality zones for the Simsima Limestone. (London)(BS 5930, 1999).

Simsima Limestone Rock Quality Zone	BS 5930:1999 Approach Weathering Zone	Proportions of Rock/Matrix	Typical Engineering Behavior
A	1-2	Rock: >90% Matrix: <10%	Behaves as rock. Apply rock mechanics principles to mass assessment.
B	3 - 4	Rock: 30-90% Matrix: 10 - 70%	.'Rock framework contributes to ' strength and stiffness; matrix
C	5	Rock <30% Matrix: >70%	Matrix controls strength, stiffness and permeability. Behaves as soil.

Through this study, (Fourniadis, 2010)utilized rock mass characterization approach in order to obtain a classification system for Simsima limestone to rock quality zones. Several parameters have been derived for each quality zone. (Fourniadis, 2010) believed that rock mass quality zones classification system can be implemented to have a more balanced and economic foundation engineering design. Coring photos for samples for the three zones are shown in figure 9.
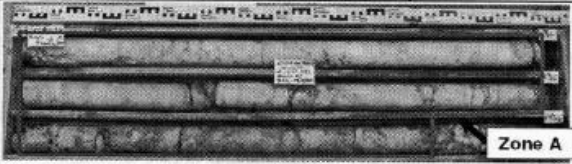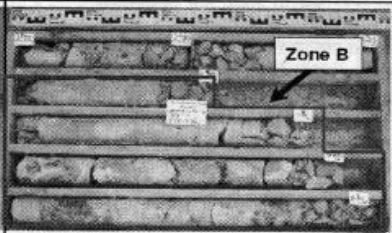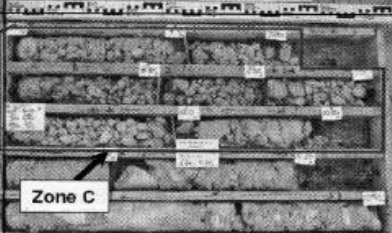
Weathering Zone	Example core photograph	Example description
A (fresh to moderately weathered rock)	Zone A Moderately strong pinkish grey LIMESTONE with some vugs (5-50mm diameter, 5-15% by volume), grey staining and locally cemented with white moderately weak to moderately strong calcitic silty material.	
B (heavily weathered rock)	Zone B	Moderately weak to moderately strong light grey fine grained crystalline weathered LIMESTONE. Closely spaced joints, heavy staining and occasional infilling of dark brown stiff clay and find grained limestone gravel.
C (matrix-dominated with some corestones)	Zone C	Recovered as non-intact gravel-sized limestone fragments in a calcitic sandy silt matrix.

Figure 9 - Coring samples for Simsima A,B, and C layers (Fourniadis, 2010).

As mentioned above, Simsima limestone is commonly found in Qatar peninsula that extends down to more than 30 meters depth that makes it the foundation layer for most of the engineering projects. Simsima limestone is considered as a type of rock with karst features and anisotropic properties as several vugs and irregular joints frequently filled with weak material. Properties of Simsima limestone vary differ notably over the depth at the same location, and in general, Simsima limestone varies in its strength between weak to strong rock (Fayed). Moreover, it is clear that classifying Simsima limestone using the point load test only is not recommended due to several reasons such as the high scatter in its index 'Is_{50}' values compared to the consequent UCS values(Fayed). Also, Fayed proposed that the procedure of classifying Simsima limestone from the strength perspective must be examined firstly by using the uniaxial compressive strength, then selecting the proper approximate correlation factor between UCS and $Is50$ values, and in case of lack UCS rock values for Simsima limestone, the bulk unit weight might be used as first indication of its strength. Moreover, hammers, Schmidt hammer and other geological

methods can give a proper classification for the rock strength in the absence of UCS values as well.

According to (Fayed), estimating the UCS values from the Is_{50} values using polynomial (quadratic and cubic) regression models are much better than linear regression over certain ranges (i.e. $Is_{50} \leq 5.0$ MPa for the quadratic model and $Is_{50} \leq 3.0$ MPa for the cubic model). One of the disadvantages of the linear regression model according to author, is the large variation of the correlation factors between the uniaxial compressive strength and the point load test index with the strength classification of rock. Moreover, in absence of UCS rock results the linear correlation factors might be used to classify Simsima limestone.

Famous phenomenon must be taken into consideration when engineers deal with the rocks that contain matrix material similar to the rocks in Qatar is "Wetting phenomenon" that is known as collapse upon wetting(Wheeler, 1994, Alonso and Gens, 1994).These researches discussed it in their literature focusing on cemented soils, as a change in the volumetric instability in the matrix material could happen due to sudden water content change. The relatively high percent in settlement that was observed by the authors leads them to state two major processes that may occur simultaneously upon wetting; i) collapse upon inundation, and ii) softening of the clay in the matrix.

Another phenomenon has to bared in mind is " Clay Set up" (Akili, 2008). Akili described this phenomenon as clay or clayey silt (Matrix Material) regain strength in a period of time as pore pressure is dissipated. This phenomenon appears in the pile driven process in several locations in Doha, when numerous piles met refusal initially but were able to be re-driven after fairly short time delay. This happens when the matrix material are found to be stiff, overconsolidated clays and dense silty sand. However, author suggested that the reduction in the driving resistance may be caused by the relaxation of the matrix material found in rock, or to the increase in the pile hammer efficiency, or a grouping of two factors.

Karst that is widespread on the peninsula of Qatar in the Arabian Gulf must be mentioned when studying of Qatar geology is taken place, kasrst that includes depression, sinkholes, caves, and solution hollows. More than 9700 large and small depressions, and several exposed sinkholes and caves are known(Sadiq and Nasir, 2002). It is found mainly in the Eocene Rus and Dammam

formations within the limestone, dolomite and gypsum. Karst features in Qatar is oriented NE-SW and NW-SE same as the joint and fracture systems. This means that rock type and existence of joints and fractures are considered the main factors developing karst in Qatar. Air photos show that karst in Qatar occurs as three types(Sadiq and Nasir, 2002); i) Sinkholes, ii) Simple depressions; with single center, and iii) Compound depression; contains more than one center, large and rectangular or irregular shaped, and seems to be created by the merging of several simple depressions.

2.4   Challenges face engineers dealing with Rocks in Qatar

Highly variability in the ground conditions have been showed from the local experts experience and borehole data results in many offshore sites. In addition of these variability, the presence of inadequate soli investigation and results in the in-situ conditions lead commonly to a significant discrepancy in deferent engineering applications (Akili 2004).

Pile installation process as a common engineering process take place in Qatar, recommendations were proposed based on (Akili and Jackson, 1998, Akili, 2008, Akili, 2009, Akili, 2004, Akili, 2000)experience and accompanied by experience American Petroleum Inst. 1991; (O'Neill and Raines, 1991, Poulos, 2005). The recommendation are divided to six main categories : i) geotechnical investigation, ii) pile characteristics, iii) hammer sizes, iv) remedial pile installation procedures, v) safety factors and pile acceptance, and vi) monitoring. All these recommendations are mandatory and have to be implemented by stakeholders in their strategy and workflow in the offshore pile installation in Gulf region. By executing a plan including these recommendations and implementing these recommendations correctly, some of the offshore pile installation problems will be solved, a significant confidence will be gained concerning the capacity of the installed piles, a reduction in the gap between the design data and the field outcome will be achieved and adequate approach will be integrated in the pile driving. Also, the heterogeneity variation, the characterizing difficulty with conservative geotechnical investigation, and the lack of general design procedures of the diagenetic limestone, are the reasons of the designers and contractors interests, especially when the shallow foundations are a probable alternative.

Form an engineering prospective, the diagenetic limestone strength and deformability are not essentially affected by: i) the relative percentage of original limestone to secondary material, ii) the physical, chemical and mineralogical compositions of the secondary material, and iii) the properties of the secondary material and in particular the degree of cementation that these materials can impart (Akili and Jackson, 1998). In this research, authors revealed that the presence of auapilgite in relatively large portions, the diagenetic limestone strength and deformability are significantly affected. The digenetic rock mass becomes weak and extremely disposed to deformation under load. The quality of the diagenetic limestone significantly varies over quite small horizontal or vertical distances (three to five meters). In a wetting/saturation case, the secondary' attapulgite becomes highly plastic which significantly reduces the strength

of the diagenetic limestone. This phenomenon is really important especially in the zones when the secondary attapulgitc percentage is higher than fifty percent of the diagenetic rock mass.

(Akili and Jackson, 1998) stated some queries have to be answered to be able to avoid the problems combined with using diagenetic limestone as foundation material, these questions are:

i) How extensive are these materials underneath a proposed structure in three dimensional space?

(ii) What are their engineering properties as they lie in the ground?

(iii) What are the stress changes to which they will be subjected?

(iv) How will the mass of material affected by the stress changes behave as the stress changes occur?

They also concluded that a systematic studies, field experiments and laboratory studies of these materials on undisturbed samples are clearly needed to correctly use diagenetic limestone as foundation material. In this research, a huge effort was done by (Akili and Jackson, 1998) to provide geotechnical information from three sites located in Doha, these locations have faced the existence of diagentic limestone in their rock formations. Plate load test data has been carried out in order to conclude the settlement with the presence of foundation geometries and allowable bearing capacities, bearing in mind field conditions in order to have design recommendations for each site. Three sites, named A, B and C which are located in Al Sadd and Old Salata areas in Doha, can be considered as similar conditions and characteristics at other sites in Qatar. Authors have focused on the presence of the diagentic limestone describing their properties and behavior, and make use of the plate load test in order to determine settlements and, thus allowable bearing capacities to help the designers to choose the most suitable foundation system for each location. Author revealed that, constructing shallow spread foundations must be avoided when it comes to deal with rocks similar to the rocks in Qatar. Especially when 'diagentic limestone' appears during excavation process. As it is very hard to predict the matrix material behavior under loading conditions, due to this, mats and strapped footings have become the favorable choice for most of the designers dealing with the rocks in Qatar. Moreover, mapping out the amount and extent of this matrix material in three dimensional space under any proposed structure will help

to get an appropriate foundation system estimating all the allowable loads acting on these systems.

In addition, Arup Geotechnics investigations applied in important project in Qatar have shown that the Simsima limestone is a variable material and its properties significantly vary over quite small distance. Also the Simsima limestone properties and characteristics vary depending on the weathering processes as dolomitization and karstic dissolution have acted on the rock mass. Moreover, photographs of high quality double and triple-tube rotary core drilling were conducted in order to investigate the weathering profile of the Simsima limestone in Qatar peninsula (Fourniadis, 2010). Results show a complex profile with highly weathered rock alternating with unaltered rock, or cavities infilled with weakly cemented carbonate and agrillaceous material. In fact, this profile is mutual for the carbonate rocks in arid environments deferent from the typical profiles of weathered or unweathered rock found in humid environments. (Fourniadis) believed that the process of zoning the founding material into the rock quality grades as described above (Table 1) with assessing the compressive strength and stiffness values for each zone can achieve and economic and proper design for any foundation system dealing with similar rock in Qatar.

2.5   Rock Sampling

Rock can be considered as a combination of minerals and grains welded together (Fayed), that fact lead us to understand that rock strength is size dependent. Therefore large rock samples are required to give a real result of the rock strength. The meaning of large samples are the samples that include microscopic cracks and fissures. Due to this, size factor has been a subject to several investigations over the last decades. Subsequently, the determination of the extent of the diagenetic limestone below a future structure has become so essential, that ambitious towards the diagenetic limestone has forced engineers and contractors to develop techniques of boring, sampling and evaluating parameters. However, from previous experience, boring into diagentic limestone often gives low core recoveries mainly with small diameter equipment and inexperienced operators. Consequently, obtaining an undistributed sample for additional tests is extremely difficult. In the presence of diagenetic limestone at shallow depth, trial pitting can be really convenient as it allows: i) visual examinations of materials encountered, ii) performance of some in-situ testing (hand-held penetrometers and plate load tests), and iii) potential recovery of block samples for tests in the undisturbed state.

2.6   Uniaxial compressive strength Test ASTM D 7012

From the rock mechanics and engineering geology perspective, the boundary between the rock and soil is defined based on the uniaxial compressive strength not based on the structure, texture or weathering conditions. The uniaxial compressive strength can be determined directly by uniaxial compressive strength tests, or indirectly from point-load strength tests. Classification of the uniaxial compressive strength suggested by ISRM (1978) is shown in Table (2).

Rock classification	UCS (MPa)
Very weak rock	1–25
Weak rock	25–50
Moderately hard rock	50–100
Hard rock	100–200
Very hard rock	> 200

Table 2 - UCS Rock classification (Deere and Miller, 1966).

ISRM (1981) defined the uniaxial strength of samples of rock of 50 mm diameter. However, the strength of rock depends on the size of the samples due to the presence of microscopic cracks and fissures (Hoek and Brown, 1980). They showed the scale effect of specimens of diameters between 10 and 200 mm and compared them with the specimens if diameter 50 mm. The relation between different diameters specimens and 50 mm diameter specimens has been derived as:

$$\sigma c = \sigma c_{(50)} \, (50/d)^{0.18} \qquad \text{Equation (2)}$$

Where,

$\sigma c_{(50)}$: is for specimens of 50 mm diameter, and

d: is the diameter (in mm) of the actual tested samples.

The chart shows a curve with equation:
$$(\sigma_c/\sigma_{c50}) = (50/d)^{0.18}$$

Y-axis: Uniaxial compressive strength of specimen / Uniaxial compressive strength of 50 mm diameter specimen ($\sigma_c | \sigma_{c50}$)

X-axis: Specimen diameter d - mm

Symbol	Rock	Tested by
○	Marble	Mog [166]
□	Limestone	Koifman [169]
▽	Granite	Burchartz et al. [169]
△	Basalt	Koifman [169]
▷	Basalt-andesite lava	Melekidze [169]
◁	Gabbro	Ilnickaya [169]
●	Marble	Ilnickaya [169]
■	Norite	Bieniawski [167]
▲	Granite	Hoskins & Horino [170]
▼	Quartz diorite	Pratt et al. [168]

Figure 10 - Specimens Size Effect on the Uniaxial Compressive Strength after Hoek and Brown, (1980).

Uniaxial compressive test is restricted and limited to the fairly hard rock specimens. Laboratory tests are the one which can classify the strength of specimens, however, simpler methods can provide fairly approximate results. Schmidt hammer and specific gravity tests can estimate the rock strength (Deere and Miller, 1966). Also the rock strength can be assessed from a full description of a rock including composition and possible anisotropy and weathering (Palmstrom, 1995) . Figure 11 shows the UCS apparatus.

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Figure 11 - Uniaxial compressive strength apparatus.

2.7   Point load test ASTM D5731

Point load strength test is performed by loading a specimen of rock between two steel plates as explained by ISRM (1985). The use of point load strength index (Is) for rock strength testing is recommended as by simple portable equipment in the field, the (Is) can be easily determined on specimens without preparation. (Broch and Franklin, 1972, Bieniawski, 1984, Fayed) revealed that performing this test has gained more importance due to the difficulty of retrieving intact samples of proper sizes for conducting uniaxial compression strength tests (UCS) in Lab. Figure 12 shows the point load test machine.

Figure 12 - Point load test machine.

2.7.1 The Point load strength index (Is_{50})

Is_{50} is the test results for 50 mm thick samples of rock (Greminger, 1982). Meanwhile Is_{50} is around 80% percent of the uniaxial tensile or Brazilian tensile strength (Palmstrom, 1995). The point load strength test is somehow a method of indirect tensile test, however, it is not relatively connected to its primary role in rock classification and strength as a tensile characterization.

2.8 Testing Experience for Rocks in Qatar

2.8.1 UCS and Point load test relation

Conventional site investigation tools usually can't extract diagenetic limestone rock suitable enough to perform UCS tests due to diagenetic limestone complex formation(Fayed). Commonly the extracted samples either in small sizes (low RQD) or disturbed in a manner of containing artificial cracks resulting from the rock coring technique, thus in such cases, the point loads strength test can be regularly used to as an indirect measure of the compressive or tensile strength of the rock. The correlation between the UCS and point load strength tests has been investigated a lot, most of the investigation focused on finding a linear relationship as a constant factor between both tests results as following equation:

$\sigma c = k \ Is_{50}$　　　　　Equation (3)

Where,

σc = Uniaxial Compressive Strength of rock (UCS).

Is_{50} = Point Load Index for 50 mm diameter core.

k = Linear correlation factor

The most common value of the factor (k) was recommended by Broch and Franklin (1972) is (k = 24). However, the constant (k) doesn't depend only on the rock type, it also depends on the rock strength classification.

Hence, in order to thoroughly study and understand the correlation between the UCS and Is_{50} values of the Simsima limestone, results of both tests from eight different sites located at different places across the Qatar peninsula were collected, classified and statistically analyzed(Fayed). Knowing that selecting the samples was a strictly filtered process in order to be approximately the same level in the Simsima limestone formation for having a reasonable comparison. Tests were performed according to ASTM: D5731-08 for the point load strength index and ASTM: D2938-95 for the uniaxial compressive strength. Several regression models (linear, quadratic and cubic) have taken place to reach the favorable approach to get the constant factor that correlate UCS to Is50 values, which differs depending on rock strength classification ranges from (4.0, 7.4 and 13.6) according to Fayed. The author has recommended not to use

point load strength tests solely for characterizing the Simsima limestone, however, he recommended to use them for preliminary assessment. In fact, Fayed believed that uniaxial strength tests (UCS) are the main tests for characterizing rocks from strength perspective, as they show the maximum strength limits for the rock masses.

2.8.2   Rock Testing in Qatar

Another study has to be mentioned here, although its topic is focusing in different topic concerning the Rus formations from a geological perspective to use it in water, oil and gas fields. It was conducted by (El-Sayed, 1987) for the Rus formation (Lower Eocene), as thirteen limestone samples were selected from four different locations in Qatar peninsula, subjecting these samples to electrical resistivity, porosity, shaliness factor and water saturation measurements.

In addition, another attempt was conducted by (Stypulkowski et al., 2014) for the rock mass found in Doha, Qatar to make a correlation between Qw , RMR and weak rock field assessment at Abu Hamour area must be mentioned hereafter. An Infrastructure project has taken place at the Abu Hamour southern outfall which can be considered a very important element in the drainage network for the greater Doha area in Qatar. The project designers have considered an area of 170 km^2 to be the covered catchment area that allows storm water runoff to flow through ground water 3.7 m tunnels excavated by TBM machine. This study has used the data gained during the TBM shaft excavation stage. Each shaft is 30 m deep, which allow the authors to have a good data resource for rock in this area. Several lab tests were conducted on the samples bored from Abu Hamour are such as: Uniaxial compressive strength with elastic modulii, point load test, indirect tensile strength, Cerchar abrasion test, macroscopic description, water soluble sulphate and chloride content of rock, carbonate content, and pH value. Also, Geophysical survey was carried out for the same area, as resistivity imaging and seismic refraction, natural gamma, electromagnetic induction, fluid conductivity, and fluid temperature were taken place in order to identify the rock condition, while packer test was conducted to determine the permeability of the rock mass. Lab tests results were as follow:

Test Name	Results
UCS	6-34 MPa (15 MPa median)
Tensile Brazilian Test	2.4-3.5 MPa (2.7 MPa median)
Is $_{50}$ from point load test	0.2-3 MPa (1 MPa median)
Young's modulus from UCS test	1-34 GPa
Down-hole seismic test	0.5-5.2 GPa

Table 3 - Laboratory results for Simsima layers at Abu Hamour area (Stypulkowski et al., 2014).

2.9   Rock Classification Systems

2.9.1   General

Rock mass classification systems are widely used in a range of purposes and projects, for instance, they could be used during the data gathering phase, or in feasibility and preliminary design stages. They provide data insights concerning rock mass stresses and hydrologic characteristics in a unified way. Other rock mass classification schemes usages include the design and estimation of support requirements, rock mass strength and deformation properties of the rock mass through visualization, and rock mass composition and characteristics.

However, it is important to understand the limitations of such classification schemes (Palmstrom and Broch, 2006). Even though rock classification schemes are beneficial, they cannot replace other conventional detailed design schemes and procedures. Rock classification schemes are mostly used during the early stages of the project, when detailed data about in situ stresses, rock properties and excavation planning schedules are available at this stage. This type of information is necessary for most design procedures. As the project progresses, more data is available, allowing the rock mass classification scheme to be updated and subsequently used together with other elaborate design procedures and in-situ specific analysis.

However, in an attempt to formalize an empirical approach in support requirements of tunnel designs, (Ritter, 1879)initially proposed the rock mass classification schemes which are constantly developed ever since. Rock mass classification schemes are considered ideal if used in compliance with their original case application, yet they can be meticulously used in any other rock engineering projects as well.

In this chapter, a brief of the most important and commonly used systems will be provided. The currentstudy covers notes and comments from the most significant works in the literature. Since the list is not exhaustive, references are also included for further in-depth analysis.

Some classification schemes were developed for past civil engineering projects such as:

- (Wickham et al., 1972)
- (Bieniawski, 1974, Bieniawski, 1989)
- (Barton et al., 1974)

These schemes included multi-parameter classification systems and listed all the main engineering components and rock mass geological characteristics.

When using a rock mass classification scheme it is highly advised to consider at least two different methods for any site, especially in the project's early stage, since classification systems focus on different rock mass parameters. The influence of water and rock mass weathering are usually negligible in deep levels of underground hard rock mining.

According to Erik Eberhardt, from the (UBC-Geological Engineering, Canada), classification system's objectives should be the following:

1. Identify the most important parameters that affect rock mass,

2. Divide the rock mass formations into groups of similar behavior,

3. Provide a basis for understanding the characteristics of each rock mass class,

4. Compare rock conditions of one site to another,

5. Provide quantitative data and guidelines for engineering designs, and

6. Provide a common basis for communication between geologists and engineers.

2.9.2   Terzaghi's Rock Mass Classification

The paper by (Terzaghi, 1946) is considered the earliest reference for potential usages of a rock mass classification system in tunnel support design. The descriptive classification was used to estimate the rock loads carried by steel sets. The Terzaghi's original paper covers mainly rock mass dominant characteristics when gravity is the main dominant driving force. The given data descriptions are considered valuable geological engineering data for engineering designs since they are precise and clear. Yet, Terzaghi's classification does not provide beneficial data for support designs. Terzaghi's descriptions (quoted directly from his paper) are:

- *Intact* rock contains neither joints nor hair cracks. Hence, if it breaks, it breaks across sound rock. On account of the injury to the rock due to blasting, spalls may drop off the roof several hours or days after blasting. This is known as a *spalling* condition. Hard,

intact rock may also be encountered in the *popping* condition involving the spontaneous and violent detachment of rock slabs from the sides or roof.

- *Stratified* rock consists of individual strata with little or no resistance against separation along the boundaries between the strata. The strata may or may not be weakened by transverse joints. In such rock the spalling condition is quite common.

- *Moderately jointed* rock contains joints and hair cracks, but the blocks between joints are locally grown together or so intimately interlocked that vertical walls do not require lateral support. In rocks of this type, both spalling and popping conditions may be encountered.

- *Blocky and seamy* rock consists of chemically intact or almost intact rock fragments which are entirely separated from each other and imperfectly interlocked. In such rock, vertical walls may require lateral support.

- *Crushed* but chemically intact rock has the character of crusher run. If most or all of the fragments are as small as fine sand grains and no re-cementation has taken place, crushed rock below the water table exhibits the properties of a water-bearing sand.

- *Squeezing* rock slowly advances into the tunnel without perceptible volume increase. A prerequisite for squeeze is a high percentage of microscopic and sub-microscopic particles of micaceous minerals or clay minerals with a low swelling capacity.

- *Swelling* rock advances into the tunnel chiefly on account of expansion. The capacity to swell seems to be limited to those rocks that contain clay minerals such as montmorillonite, with a high swelling capacity.

2.9.3 Classifications involving stand-up time

In order to clarify the concept of the stand-up time of any unsupported span, it is important to define the unsupported tunnel spanning which refers to the largest distance between the face and the closest support. There is a relation between the stand-up time of an unsupported span and the quality of the rock mass. The span can be excavated if the unsupported span is larger than the tunnel's one, as proposed by Lauffer (1958) in his original classification. Many authors modified Lauffer's work such as: (Pacher et al., 1974). This updated work is now part of the New Austrian Tunneling Method which describes a general tunneling approach.

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However, the main importance of the stand-up time concept is that longer tunnel spans require early supporting system installation. In other words, in the case of two tunnels excavated in the same rock mass, with the one being a small pilot and the other having a large span, the first one might require basic support but the latter one may not be stable without an immediate substantial support.

Furthermore, the new Austrian Tunneling Method defines techniques for ensuring safe tunneling processes in different rock mass conditions, especially for short stand-up times where safe tunnel time is limited. Some of these techniques are the following:

- Usage of smaller headings and benching

- Usage of multiple drifts to formulate a reinforced ring where the tunnel can be interiorly excavated.

These techniques can be used in soft rock masses like Phyllites, shales and Mudstone. These types of rock masses are also known to have squeezing and swelling issues as mentioned by Terzaghi (mentioned in the previous section). In addition to these rock masses types, these techniques can be used when facing broken rock masses. In contrast, these techniques must be used with great caution when facing hard rocks, where different failure mechanisms are apparent.

The same study suggests that in cases of hard rock excavations, the designer of the support should assume that the rock mass stability is not time dependent, therefore, a supporting system removal might trigger an immediate failure in the roof of the excavation in a structurally exposed wedge. This failure can take place during a scaling operation or a blast. Installing the support system as early as possible, even before removing the rock that supports the full wedge, is crucial when the wedge is required to be kept or for increasing the safety margin. In contrast with hard rock, the highly stressed rock will fail due to stress field changes surrounding the excavation. In this case, failure can be sudden in the form of rock burst or progressive after spalling or slabbing. For both cases, the governing factor in highly stressed rocks is the stress field change and not the stand-up time of the excavation.

2.9.4 Rock Structure Rating (RSR)

Rock structure rating is a quantitative method for describing the quality of rock mass and for selecting suitable support, proposed by Wickham et al.,(1972). Past cases were used for defining the RSR but included relatively small tunnels with steel supporting systems. Yet, this rating was a pioneer for making a reference to shotcrete supports. The RSR system reveals the logic of a quasi-quantitative rock mass classification system, making it worth of study even its several limitations.

The RSR system introduced the concept of rating the following components to formulate the numerical value of RSR = A + B + C (Wickham et al., 1972):

1. *Parameter A, Geology:* General appraisal of geological structure on the basis of:

    a. Rock type origin (igneous, metamorphic, and sedimentary).

    b. Rock hardness (hard, medium, soft, and decomposed).

    c. Geologic structure (massive, slightly faulted/folded, moderately faulted/folded, intensely faulted/folded).

2. *Parameter B, Geometry*: Effect of discontinuity pattern with respect to the direction of the tunnel drive on the basis of:

    a. Joint spacing.

    b. Joint orientation (strike and dip).

    c. Direction of tunnel drive.

3. *Parameter C*: Effect of groundwater inflow and joint condition on the basis of:

    a. Overall rock mass quality on the basis of A and B combined.

    b. Joint condition (good, fair, poor).

    c. Amount of water inflow (in gallons per minute per 1000 feet of tunnel).

It is noted that RSR classification system uses imperial units and these units are retained in this discussion.

Three tables from Wickham et al's (1972) research are reproduced in Tables (4), (5) and (6). These tables can be used to evaluate the rating of each of these parameters to arrive at the *RSR* value (maximum *RSR* = 100).

	Basic Rock Type					Geological Structure		
	Hard	Medium	Soft	Decomposed				
Igneous	1	2	3	4		Slightly	Moderately	Intensively
Metamorphic	1	2	3	4		Folded or	Folded or	Folded or
Sedimentary	2	3	4	4	Massive	Faulted	Faulted	Faulted
Type 1					30	22	15	9
Type 2					27	20	13	8
Type 3					24	18	12	7
Type 4					19	15	10	6

Table 4 - Rock Structure Rating: Parameter A: General area geology (Wickham et al., 1972).

	Strike ⊥ to Axis					Strike ‖ to Axis		
	Direction of Drive					Direction of Drive		
	Both	With Dip		Against Dip		Either direction		
		Dip of Prominent Joints [a]				Dip of Prominent Joints		
Average joint spacing	Flat	Dipping	Vertical	Dipping	Vertical	Flat	Dipping	Vertical
1. Very closely jointed, < 2 in	9	11	13	10	12	9	9	7
2. Closely jointed, 2-6 in	13	16	19	15	17	14	14	11
3. Moderately jointed, 6-12 in	23	24	28	19	22	23	23	19
4. Moderate to blocky, 1-2 ft	30	32	36	25	28	30	28	24
5. Blocky to massive, 2-4 ft	36	38	40	33	35	36	24	28
6. Massive, > 4 ft	40	43	45	37	40	40	38	34

Table 5 - Rock Structure Rating: Parameter B: Joint pattern, direction of drive (Wickham et al., (1972).

	Sum of Parameters A + B					
Anticipated water inflow	13 - 44			45 - 75		
	Joint Condition [b]					
gpm/1000 ft of tunnel	Good	Fair	Poor	Good	Fair	Poor
None	22	18	12	25	22	18
Slight, < 200 gpm	19	15	9	23	19	14
Moderate, 200-1000 gpm	15	22	7	21	16	12
Heavy, > 1000 gp	10	8	6	18	14	10

[a] Dip: flat: 0-20°; dipping: 20-50°; and vertical: 50-90°
[b] Joint condition: good = tight or cemented; fair = slightly weathered or altered; poor = severely weathered, altered or open

Table 6 - Rock Structure Rating: Parameter C: Groundwater, joint condition (Wickham et al., 1972).

Drive with dip

Drive against dip
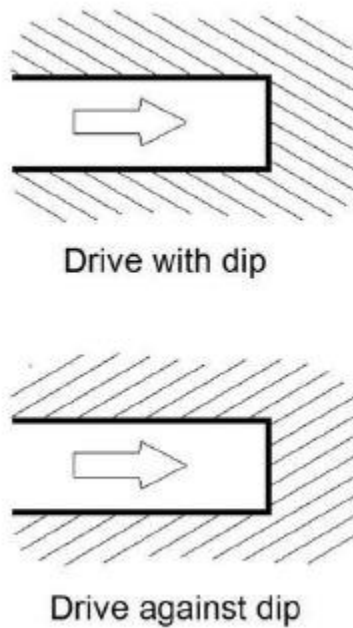
Figure 13 - Joints orientation (Wickham et al., (1972).

Nowadays, the RSR classification system is not often used, since several parameters related to the rock mass properties are neglected in the calculation, yet the work of Wickham et al., (1972) significantly contributed to the development of several future classification systems which are discussed next in this chapter.

2.9.5 Rock Mass Rating RMR

The Geo-mechanics classification system, or most commonly known as Rock Mass Rating (RMR) system, was proposed by the Polish scientist Bieniawski, (1976). Bieniawski who

graduated at the University of the Witwatersrand in Johannesburg, South Africa, introduced many novelties in the assigned ratings. The system included various additional parameters and has been modified and improved over the years due to the increasing number of case studies. The (1989) version is the one used in the evaluation which estimates the rock mass strength. The classifying parameters of the RMR are as follows:

1. Uniaxial compressive strength of rock material.

2. Rock Quality Designation (*RQD*).

3. Spacing of discontinuities.

4. Condition of discontinuities.

5. Groundwater conditions.

6. Orientation of discontinuities.

Dividing rock mass into a number of structural regions and classifying each region separately, is the first step required when applying the RMR classification system. A structural region boundary with major structural features interference might be realized in cases such as a fault or change in rock type. Thus, it is crucial to divide a single rock type into smaller structural regions due to significant discontinuity changes in spacing or characteristics

In Table (7), a presentation of the Rock Mass Rating system is shown with ratings for every parameter of the previous list. The summation of these ratings is the value of RMR. The usage of these tables is emphasized with the following example to reach the value of RMR.

	PARAMETER		RANGES OF VALUES						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 -10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range – uniaxial compressive test is preferred		
		Uniaxial compressive strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 MPa	1-5 MPa	<1 MPa
		Rating	15	12	7	4	2	1	0
2	Drill core quality RQD		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		>2 m	0,6 - 2 m	200 - 600 mm	60 - 200 mm	<60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces. Not continuous No separation Unweathered wall rock.	Slightly rough surfaces. Separation < 1 mm Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm Highly weathered walls	Slickensided surfaces OR Gouge < 5 mm thick OR Separation 1-5 mm. Continuous	Soft gouge > 5 mm thick OR Separation > 5 mm. Continous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length	None	<10 litres/min	10-25 litres/min	25 - 125 litres/min	>125		
		Ratio (joint water pressure / major principal stress)	0	0,0-0,1	0,1-0,2	0,2-0,5	>0,5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

Table 7 - RMR classification table (Bieniawski, 1989).

Based on the final determined RMR value, a set of tunnel guidelines for rock support selection process was published by Bieniawski (1989). These guidelines are intended for tunnels constructed using drilling and blasting methods with a span of 10 m and a horseshoe shape. Their rock mass is estimated to be subjected to a vertical stress < 25 MPa (equivalent to a depth below surface of < 900 m). These guidelines are available in Table 8.

Rock mass class	Excavation	Rock bolts (20 mm diameter, fully grouted)	Shotcrete	Steel sets
I - Very good rock RMR: 81-100	Full face, 3 m advance.	Generally no support required except spot bolting.		
II - Good rock RMR: 61-80	Full face, 1-1.5 m advance. Complete support 20 m from face.	Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh.	50 mm in crown where required.	None.
III - Fair rock RMR: 41-60	Top heading and bench 1.5-3 m advance in top heading. Commence support after each blast. Complete support 10 m from face.	Systematic bolts 4 m long, spaced 1.5 - 2 m in crown and walls with wire mesh in crown.	50-100 mm in crown and 30 mm in sides.	None.
IV - Poor rock RMR: 21-40	Top heading and bench 1.0-1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face.	Systematic bolts 4-5 m long, spaced 1-1.5 m in crown and walls with wire mesh.	100-150 mm in crown and 100 mm in sides.	Light to medium ribs spaced 1.5 m where required.
V – Very poor rock RMR: < 20	Multiple drifts 0.5-1.5 m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting.	Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mesh. Bolt invert.	150-200 mm in crown, 150 mm in sides, and 50 mm on face.	Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert.

Table 8 - Guidelines for excavation and support of 10 m span rock tunnels in accordance with the RMR system after (Bieniawski, 1973).

Data of Table (8) is not updated significantly since 1973. Steel fiber reinforced shotcrete may replace the wire mesh and shotcrete in many mining and civil engineering applications.

2.9.5.1 Modifications to *RMR* for Mining

Rock Mass Rating was mainly developed for civil engineering purposes and was based upon past civil engineering applications, yet the mining industry considered also to use this classification scheme after applying several restrictive modifications for addressing mining applications. These modifications were summarized by Bieniawski (1989).There are two main modification processes applied to the basic RMR to match the mining activities and are the following:

- The Modified Rock Mass Rating (MRMR) system for mining was described by many authors such as Laubscher (1977, 1984), Laubscher and Taylor (1976) and Laubscher and Page (1990). The MRMR adjusts the basic RMR value, as described by Bieniawski, for matching the effects of blasting and weathering, the stress changes, and the in situ and induced stresses. The resulting MRMR value is also associated with a set of support

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recommendations. Laubscher's MRMR system was developed examining past caving operations, such as African asbestos mines and block caving and including later several other cases from around the world.

- The Modified Basic RMR (MBR) is a modification applied on the basic RMR system to match the mining systems, it was introduced by Cummings et al., (1982), and Kendorski et al.,(1983). The addressed modifications are based on case studies of block caving applications in the United States of America. In this system, different RMR parameter ratings were used along with adjustments for allowing the MBR value to consider additional parameters such as blast damage, structural features, size of the caving block, induced stresses, and distance from the cave front. In this system, support recommendations for isolated, development drifts, and final intersection supports and drifts are available.

2.9.6   Rock Tunneling Quality Index, Q

Barton et al.,(1974)from the Norwegian Geotechnical Institute, introduced the notion of Tunneling Quality Index (Q) based on a large number of evaluated underground excavations. It can be used to determine rock mass characteristics and tunnel support requirements. The numerical value of the Q index varies from 0.001 to a maximum of 1,000 and is defined by:

$Q= RQDJn \times JrJa \times JwSRF$ $\qquad$ Equation (4)

Where,

RQD is the Rock Quality Designation

Jn is the joint set number

Jr is the joint roughness number

Ja is the joint alteration number

Jw is the joint water reduction factor

SRF is the stress reduction factor

Barton et al.,(1974) provided an explanation of the meaning of the parameters used in the determination of the value of Q as follows:

- The first quotient (RQD/Jn), representing the structure of the rock mass,

- The second quotient (Jr/Ja), represents the roughness and frictional characteristics of the joint walls or filling materials,

- The third quotient (Jw/SRF), consists of two stress parameters. SRF is a measure of: 1) loosening load in the case of an excavation through shear zones and clay-bearing rock, 2) rock stress in competent rock, and 3) squeezing loads in plastic incompetent rocks. It can be regarded as a total stress parameter. The parameter Jw is a measure of water pressure.

Obviously, tunneling quality is affected by the following parameters; Block size (RQD/Jn), inter-block shear strength (Jr/Ja), and active stress (Jw/SRF) (Barton et al 1974).

2.9.7 Geological Strength Index GSI

Hoek (1994) introduced the concept of Geological Strength Index (GSI) in which several factors are correlated differently compared with schemes like the Q or RMR systems. Even though it was not initially considered as a rock mass classification system, it definitely reflects the rock mass quality as it deals with rock lithology, geologic structure, and discontinuity characteristics. The GSI value considers these factor in its estimation and is used in the parameter estimation of the Hoek-Brown strength criterion (Hoek et al., 2002). GSI is also used to estimate the decrease in rock mass strength for different geological conditions. However, GSI classification system can be considered a rock classification system only from a geological perspective and is sparsely used in civil engineering applications.

2.9.8 RESULTS

Rock mass classification is conducted in order to evaluate expected engineering and geotechnical behavior (i.e., stand-up time and rock support requirements) based on empirical data correlations (Najafi, 2013). Among the several rock mass classification schemes, the most commonly used is the RMR by Bieniawski (1976, 1989) and Q by Barton et al., (1974), as both consider numerous parameters such as geological, geometric, and design engineering ones that incorporate to a final quantitative value of the rock mass quality. These exploit almost the same parameters, but their major difference lies in the weight contribution of each parameter.

Obviously, the major difference between the two is that the RMR system does not consider the stress parameter. A minor difference is that the RMR system directly incorporates the compressive strength, while the Q system only incorporates the strength, since it has a direct

relation with the in situ stress in the competent rock. A lot of similarities can be found between them such the exploitation of geological and geometrical natures of the rock mass, even though they address them in different ways. Another similarity is the fact that they both consider some groundwater components in the rock material strength. In the Q system an estimation of the orientation can be included using the guidelines introduced by Barton et al (1974), while the parameters *Jr* and *Ja* relate the surface that is most likely to initiate a failure.

Generally, when using the RMR or Q frame works two different application approaches can be considered:

- Rock mass evaluation for each individual parameter.

- Initially, a rock mass characterization following a parameter attribution rating. This approach is preferable since it provides a thorough description of the rock mass allowing an efficient classification index.

If the rating values are recorded separately during the mapping, any verification study would be impossible (Hoek and Diederichs, 2006).

Moreover, the RMR and Q systems are considered adequate for planning phases of tunneling projects, where support requirement assessment such as core logging, refraction seismics and field mapping are required. When planning a cavern construction, location details could be altered by the results. Furthermore, when construction processes take place, evaluation is critical since the selection of appropriate support class takes place in daily basis (Erik Eberhardt, UBC-Geological Engineering). Both RMR and Q systems play a significant role in construction according to Erik Eberhardt:

1)   RMR and Q initially developed and updated for tunnel support estimation.

2)   Numerical modeling for rock mass properties estimation proved to be a competitive alternative to expensive and complex in situ tests that rely on several assumptions for data interpretation. Instead, the RMR and Q systems provide realistic estimations for modeling purposes, and through seismic measurements and interpretations, they can also assist in the interpretation of the disturbed zone characteristics.

3)   Using the one or even both rock mass classification methods during construction is essential in order to quantify the encountered rock mass conditions, to select the appropriate support class, and to solve possible contractual disputes, arbitrations and design changes.

4)   RMR and Q were found to be equally effective in very poor rock masses and in very good rock masses. A possible mistake would be to state that alternative descriptive methods might be preferable in poor rock mass conditions. As geological engineering techniques are improved over time utilizing advanced technology, quantitative rating systems will be always preferred against qualitative descriptive assessments.

In order to avoid confusion, Erik Eberhardt introduced several broad principle recommendations for proper usage of RMR and Q systems:

1. Ensure that the classification parameters are quantified (measured, not just described), from standardized tests, for each geologically designated structural region, employing boreholes, exploration adits and surface mapping, plus seismic refraction for interpolation between the inevitably limited numbers of boreholes.
2. Follow the established procedures for classifying the rock mass by RMR and Q and determine their typical ranges and the average values.
3. Use both systems and then check with at least two of the published correlations of Bienawski (1989) and Barton (1974).
4. Verification and changing the design could take place due to the RMR and Q mapping during the construction processes, as the expected conditions do not always match the actual conditions.
5. Laboratory tests must be incorporated and performed diligently in accordance with the standard procedures and with a decent budget. Good communication between the team of engineers and geologists and the client is a must and should be on regular basis.

2.10   RQD%: A Classification System and Rock Parameter

Deere et al.,(1969) provided a quantitative estimation of the rock mass quality from drill core logs knows as the Rock Quality Designation Index (RQD). RQD is the percentage of the intact core pieces longer than 100mm (4 inches) in the core's total length. The minimum core should be NW size (54.7 mm or 2.15 inches in diameter) and it should be drilled with a core barrel with a double tube. In Figure (14), a summary of the correct procedures in measuring the core pieces length and the calculation of RQD.

$$RDQ = \frac{\Sigma \text{Core pieces} > 10 \text{ cm}}{\text{Total length of core run}} \times 100$$

$$RDQ = \frac{38 + 17 + 20 + 35}{200} = 55\%$$
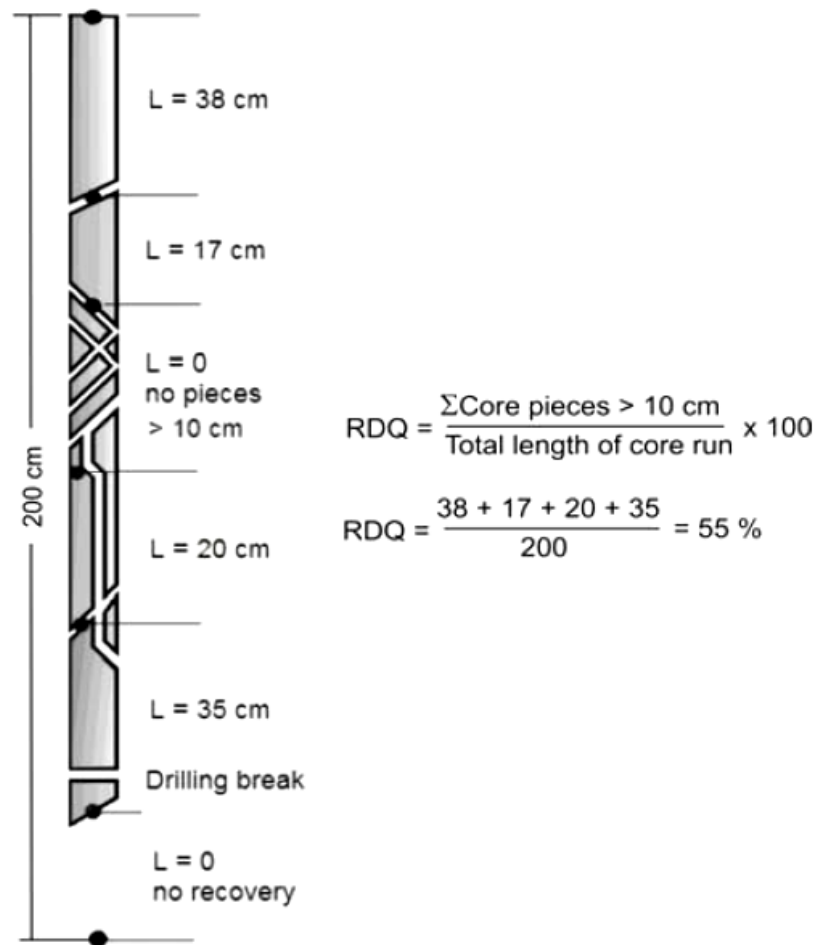
Figure 14 - Procedure for measurement and calculation of RQD after (Deere et al., 1969).

The RQD could be estimated from the number of discontinuities per unit volume in case of the absence of a core and the surface visibility of discontinuity traces exposures or exploration adits as recommended by Palmström (1982). The clay-free rock masses relationship suggestion is:

RQD = 115 - 3.3 *Jv*   Equation (5)

Where, *Jv* is the sum of the number of joints per unit length for all joint (discontinuity) sets known as the volumetric joint count.

The Value of RQD could change significantly with according to the borehole orientation as it is a dependent parameter. It could be beneficial to use the volumetric joint count in reducing the directional dependence of RQD. In case of using a diamond drill core the fractures caused by drilling and handling process should be identified and ignored in determining RQD value since it is representing the rock mass quality in situ. Also, the fractures induced by blasts should be ignored when estimating Jv while using the exposure mapping of Palmström's relationship.

In addition, RQD is used as a component of the RMR and Q rock mass classifications mentioned previously after the attempts made by Cording and Deere (1975), Merritt (1975), and Deere and Deere (1988) to relate RQD to Terzaghi's rock load factors and to the rockbolt requirements in tunnels. It was used mainly in North America. Moreover, RQD is considered as a major parameter govern the output value in the RMR system, and it was stated by Steve Hencher (2013)that RMR is used (as is RQD by itself) to correlate with rock mass parameters, including the rock mass strength and deformability, which reflects the importance of the RQD as a rock mass parameter.

2.11   Tunneling Technique

2.11.1 General

In this research, tunneling is one of the two important civil applications that were evaluated based on recorded productivities in different rock layers at several locations across Qatar. The importance of trenchless excavation has been significantly increased due to the needs of utility service lines with low ground surface disruption (Hegab and Salem, 2010). Generally, tunneling is considered a conventional trenchless technique across the world. Open-cut techniques were preferred ten years ago for their low risk and cost, with tunneling being used only where no other possible alternatives existed. Tunneling process can provide the following advantages according to Fourie, A. W. F., (2006):

- Minimizing traffic disruption,
- Minimizing subsidence,
- Avoiding relocation of existing services, and
- Personnel safety.

During the years, the confidence in tunneling techniques has been increased due to the numerous successful projects. Furthermore, engineers are yet more experienced with tunneling being among the available solutions, and found more often in contractor offers.

2.11.2 Microtunneling

It is critical to present a tunneling category which utilizes smaller tunneling machines namely the Microtunneling. Microtunnelling is a trenchless excavation method that can satisfy the needs for utility service lines with fewer surface disruptions applying remotely controlled pipe jacking. Microtunneling definition can differ depending on the country used since Europe and Japan define a pipe jacking machine as a micro-tunneling machine by its size. In Japan, machine sizes below 800 mm are considered as micro-tunneling machines while the threshold in Europe is 1,000 mm (Thomson, 1993). American contractors consider any remotely controlled guided pipe jacking machine as a micro-tunneling machine (Salem and Hegab, 2001). Moreover, Komatsu was the first vendor to develop microtunneling machines in Japan in 1972, and by the year of 1974, the first microtunneling project was successfully completed. Micro-tunneling popularity was initially limited and was finally adopted in Europe and especially in Germany and the

United Kingdom in1981 and 1984, respectively(Thomson, 1993). Microtunneling can be found in different applications such as: gravity and pressure lines, permanent ducts for cables, and railway roads under crossings. Additionally, microtunneling techniques appeared in the United States during1984 (Atalah and Hadala,(1996), and since their start, a rapid increase against open cut methods was recorded due to the following reasons (Hegab and Salem, 2010):

- High benefit-cost ratio of Microtunneling,

- Better traffic control,

- Lower reinstatement costs,

- Less need to dig around existing utilities, and

- Lower social cost.

Low social cost stands for the decrease in traffic delay time and commercial activities interruption (McKim and Turner, 1997).

2.11.3 Tunneling Operation

Despite the tunneling technique usage since 1984 in the United States, Hegab and Salem (2010) suggest that factors affecting the process success are still not very apparent to the involved parties. It is believed that any proposed project lives and dies by the quality of its field investigation (Norbury, 2010), and trenchless (tunneling) projects are no exception. Moreover, a site investigation typically requires an advance search for existing data, also surface/subsurface investigation program have to be performed subsequently, as well as an instrumentation program (Najafi, 2013). Such critical understanding will definitely lead to higher productivities of the tunneling projects. Correctly predicting the microtunneling productivity is considered as one of the main key factors for success, Iseley and Gokhale (1997) limited the main contactors' concern in predicting the underground behavior of the microtunneling machine. Contractors from their side have not recognized any productivity prediction method for microtunneling machines since machine manufacturers have not provided any production rates. Due to this, cost estimation process introduces more risks, since contractors are asked to use their own experience for such a prediction. As a result, the need for providing a reliable prediction tool to contractors for productivity expectations in different soil types has been raised. A model proposed by Hegab

(2003)included penetration, pipe segment preparation, and delay times as the basic time components for a detailed total production time estimation. Furthermore, statistical models were developed by Hegab, Smith and Salem (2006) to represent the soil penetration rate of microtunneling machines.

Hegab, Smith and Salem (2006)have defined the speed of microtunneling machines through soil types, which is equal to the penetration time per unit length. More precisely, the tunneling machine can accelerate due to the force difference acting on the machine in the acceleration direction. Acting forces are classified as following Hegab, Smith and Salem (2006):

- Jacking force hydraulic system: responsible for pushing the tunneling machine through the soil.

- Shearing force hydraulic system: responsible for the machine cutter head rotation and the steering cylinders movements.

- Friction force: which occurs due to the friction between the machine and the soil.

The combination of the two hydraulic forces minus the friction force gives the effective force that allows the tunneling machine to penetrate the soil.

Fourie, A. W. F.,(2006) noted a major shift into tunneling and microtunneling adoption especially from big construction companies in both Australia and New Zealand. Contractor competition is also a positive contributing factor. Based on his experience, Fourie summarized the factors that can determine the level of achieved productivity on tunneling and microtunneling projects and are:

- Machine configuration,

- TBM power and speed range,

- Cutter head design,

- Water treatment,

- Face pressure control and material/slurry flow,

- Control issues,

- Inter-jacking speed,

- Annular lubrication,

- Site logistics, and

- Equipment maintenance.

According to Fourie and as mentioned above, the most important factor that affects tunneling techniques is machine's configuration, which mainly depends on the soil condition and the accurate soil investigation reports analysis for proper machine selection. Contractors also need to have a clear understanding of all the key issues and their influence in machine selection process. A summary of some of these issues according to Fourie, A. W. F., (2006) are given below:

- Type of soils: This will often vary through the drive. A critical analysis of the requirements for each type and how the machine will cope with each is required.

- What is the particle size distribution? A large % under 20 microns will push up water treatment costs considerably.

- Are there any cobbles present? This will determine whether or not a crusher is required.

- How hard are the formations to be tunneled through and is it fractured or not? This will determine whether or not a hard rock capable machine is required and with or without face access.

- Will tunneling be through running sands or clays? This will determine whether an open face machine is viable and will influence the cutter head design.

- Are timber/old trees or other obstacles likely to be encountered? Certain configurations are better suited to dealing with timber obstacles.

- What is the ground water situation like: Under the water table or could large pockets of water be encountered? This would rule out, or at least limit, the use of open face equipment.

Another factor that composes the productivity determinants is water treatment (Fourie, A. W. F., 2006), as slurry microtunnelling can be the bottleneck in the "production line" when unable to sustain high advance rates for long periods of time. In such bottlenecks, the slurry becomes too heavy and slows down the progress. Fourie imposed three basic approaches to deal with slurry separation:

- Discard and replenish: Completely discarding heavy slurry and replacing with fresh water is a practice which has become almost universally uneconomical and environmentally unacceptable.

- Gravity settling: Where space and environmental conditions allow large settling ponds may be used as traps, clean fluid is then skimmed off the top. In urban tunneling this low cost approach is normally not an option.

- Mechanical separation: A slurry treatment plant is used, generally consisting of scalping screens, hydro cyclones and centrifuges, alternatively clarifier tanks and belt presses. (Ben Clark, 2009).

It is obvious that when choosing the most adequate slurry plant it can deal with high silt percentages, with rocks with cohesive materials and with any type of soil. If this process is done properly, slurry microtunnelling becomes not only a very productive process but also a low-risk alternative.

As mentioned above, penetration time of tunneling machines can be predicted using mathematical models. Researchers, Hegab, Smith and Salem (2006) developed such models from tunneling contractors' real recorded data from 35 microtunneling projects between 1997 and 2002. Four different contractors were studied using six different microtunneling machines. The data was retrieved from machines' logs and operators' reports. The produced models can be applied only to drives less than 400 meters length, to machine diameters rangingfrom 400 mm to 1760 mm, to jacking forces up to700 tons, and to shearing forces less than 300 tons. The collected log sheets and operator reports include the following data; machine diameter, soil type, machine manufacturer, jacking force, cutter head torque, tunneled length, penetration time, and project data. The study examined soil penetration based on the following variables:

- Shear force of the cutter head (T) in metric tons,

- Jacking force (P) in metric tons,

- Diameter (D) in meters, and

- Jacking length (L) in meters.

With the tunneling time (TM) being the dependent variable through different soil types expressed in minutes. The chosen clustering technique that was used in the obtained data was the K-means technique. Data was clustered into three groups with their descriptive statistics shown in following Table (9). Moreover, authors divided the soil types into three categories as shown in Table (9).The undrained shear strength (qu) represents the shear strength in Clay and Silt, while the compressive strength and angle of internal friction (Ø) are considered in granular soils such as sand. In addition, soil categories were separated according to their shear strength approximate limits (Day, 2001), and described in table (9).

Cluster Centroid				
Variable	Soil type A	Soil type B	Soil type C	Grand centroid
Penetration time/length	23.8124	34.6138	57.0414	35.0336
Shear force	102.2077	115.0748	125.9165	111.1008
Jacking force	64.7237	419.326	226.5964	171.2781
Number of observations	6362	2,001	3,282	—

	Cohesive soil		Granular soil	
Soil type	Type	q_u	Type	φ
A	Soft	<0.05 MPa (1,000 psf)	Loose	<30°
B	Medium	0.05–0.1 MPa (1,000–2,000 psf)	Medium	30°–36°
C	Hard	>0.1 MPa (2,000 psf)	Dense	>36°

Table 9 - Descriptive Statistics of Data Clusters (Hegab, Smith and Salem, (2006).

Hegab, Smith and Salem (2006) developed models that reached a prediction error of about 10% improving the prediction process of microtunneling productivity for the involved contractors. Moreover, these models can be used also in tunneling quality control during bidding phases for

projects containing similar soils. However, they do not consider rocks layers, indicating a weakness point for this research.

Furthermore, a questionnaire was prepared by Hegab and Salem,(2010) for microtunneling experts to study the factors that mostly influence the tunneling process and their ranking priorities. Participants included engineers, tunneling contractors and manufacturers from United States and Canada. This research helped tunneling contractors to recognize the productivity factors since it modeled the basic productivity after evaluating the microtunneling experts' feedback.

Generally, tunneling profitability increases by realizing higher productivities but such productivity prediction is challenging because of the large number of factors that affect the process. These factors were studied based on tunneling experts' opinions Nido (1999). A questionnaire was sent to six experts requesting their comments and opinions upon productivity influential factors. Although this work did not evaluate factors' ranking importance and did not examine their relations, it still remains one of the leading works in the tunneling field. Table (10) shows the factors that affect the tunneling productivity according to Nido (1999).

Factor number	Factors affecting productivity (Nido 1999)
1	Cutter head
2	Crew/operator experience
3	Soil conditions
4	Drive length
5	Separation equipment
6	Pipe section length
7	Shaft design (size, layout, structural integrity)
8	Slurry flow rate
9	Pipe material
10	Use of IJS
11	Use of high pressure water jets at the excavation face (jetting)
12	Accurate geotechnical investigations
13	Depth of installation
14	Groundwater conditions
15	Appropriateness of the MTBM
16	Obstruction or unusual soil conditions
17	Restrictions to working hours
18	Straight versus curved alignment
19	Technical support
20	Use of lubrication

Table 10 - Proposed Microtunneling Productivity Factors (Nido, 1999).

Hegab and Salem (2010)presented survey results which studied and analyzed these factors for understanding their relative importance and for improving model's prediction. Three categories were studied in this research and included the factors that affect productivity, their dependency, and the favorable soil condition, since soil condition is also a main contributing factor (Nido, 1999).

Hegab and Salem (2010)aimed also to identify the most important factors for tunneling process derived from a conducted phone pilot survey that included contractors, engineers and

manufacturers in the microtunneling industry. Ten experts with approximate 20 years of microtunneling experience participated in the survey and revealed the involving factors that were in compliance with Nido's identified factors. Two more factors were added to Nido's list, which were the jacking thrust and cutter head torque. The following table (11) lists all the combined factors.

Table 11 - Productivity Factors from questionnaire (Hegab and Salem, (2010).

Factor	Notation	Number	Explanation	Measure	Weighted scale	Absolute deviation	Row scale
Soil condition	ST	3	Actual soil type	Sand, clay, silt	4.77	0.45	4.70
Geotechnical investigation	GI	12	Intensive borings helps in recognizing the soil type	Intensive, shallow	4.73	0.39	4.74
Operator experience	E	2	Operator's and crew experience in similar projects	Low, high	4.48	0.54	4.52
Obstructions	O	16	Existence of obstruction during tunneling	Y/N	4.43	0.58	4.55
Lubrication	L	20	Using of lubrication during tunneling	Y/N	4.16	0.68	4.22
Torque[a]	T	22	Rotating cutter torque	KNM (lb·ft)	4.10	0.38	4.25
Jacking thrust[a]	P	21	Jacking thrust and its maximum limit	KN	4.00	0.0	4.00
Separation equipment	SE	5	Configuration of separation equipment	Number of stages	3.86	0.85	3.87
Curved alignment	SC	18	Existence of curved alignment	% of curves	3.83	0.96	3.83
M/T type	M	15	Using the appropriate machine (slurry or EPB)	Slurry or EPB	3.78	0.65	3.86
Cutter shape	C	1	Shape of the cutting tool	Teeth, disks, mixed	3.72	0.99	3.86
Drive length	D	4	The tunneling length	M (ft)	3.59	0.72	3.70
Use of IJS	IJ	10	Using IJS to increase jacking length	Y/N	3.47	0.81	3.48
Technical support	TS	19	Existence of representative of machine's manufacturer	Y/N	3.36	0.82	3.36
Working hours	W	17	Number of shifts per day	1, 2, 3	3.34	0.86	3.32
Slurry rate	S	8	Pumping rate of slurry during tunneling	M3/HR	3.28	0.74	3.39
Water jetting	J	11	Using of jets in front of head	Y/N	3.15	0.90	3.26
Shaft design	SD	7	Shaft size and shape	Narrow, wide	2.95	0.69	3.13
Ground water	GW	14	Existence of ground water during tunneling	Above, below, through	2.88	0.75	3.17
Pipe length	PL	6	The used pipe length	Short, long	2.79	0.84	3.04
Pipe material	PM	9	Material type of jacked pipe	VCP, concrete, steel, GRP, PVC	2.72	0.81	2.91
Installation depth	ID	13	How deep is the pipe underground	Deep, shallow	2.48	0.81	2.70

[a]These factors are introduced by the pilot survey.

In this research, a questionnaire prepared by the authors was distributed to 82 tunneling contractors, engineers, and manufacturers across the United States and Canada. This questionnaire was also posted as an interactive form on the internet. This questionnaire contained four main sections and asked for the respondents' name, the type of business, the related work experience, the productivity factors along with their ranking of importance, the dependency between these, and finally the favorable ranked soil conditions in the microtunneling process. From the twenty seven responses, researchers were 95% confident that the rankings of the

factors represented the population opinion with +/- 15% mean confidence interval (Thompson and Seber). In addition, the respondents' distribution included eight contractors, two subcontractors, eight engineers, and five manufacturers, with 8 years of average experience, which enriched the results of the survey.

According to the conducted survey, the most influential identified factors on microtunneling productivity are the following(2010):

- Soil conditions,

- Accurate geotechnical investigations,

- Crew experience,

- Obstructions,

- Cutter head torque,

- Use of lubrications, and

- Capacity of main jacks.

The research revealed that accurate predictions of soil conditions from concentrated soil investigations lead to better project's productivity estimation. More precisely, soil conditions presented the highest rank, affecting the tunneling operations with an average score of 4.77 with MAD of 0.45.A 0.45 MAD value corresponds to opinions ranging 0.45 from the average score. As a result, it is clear that contractors have to pre-study the soil before the bidding stage, highlighting the importance of soil investigations reports during this phase. Figure (15) shows the ranking score of all the affecting factors.
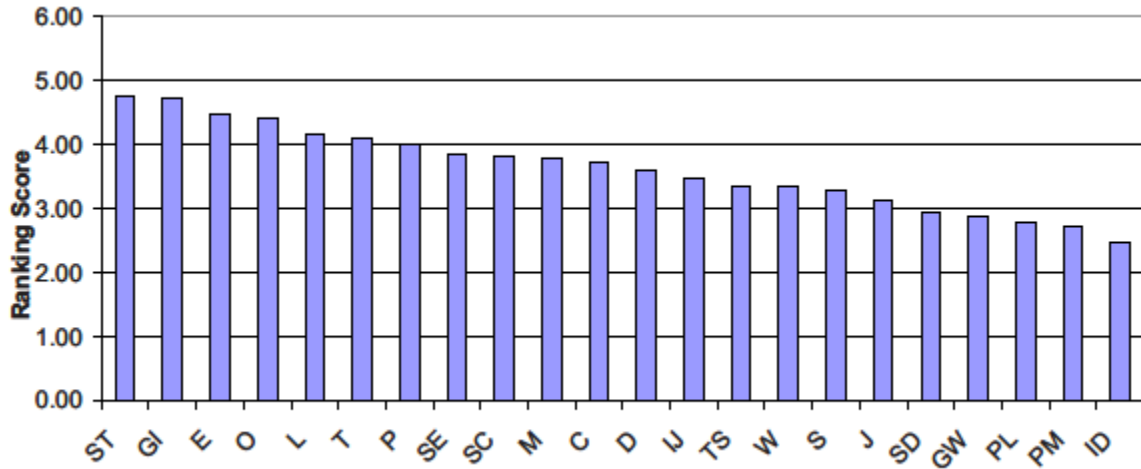
Figure 15 - The most affecting on Microtunneling productivity ranking score (Hegab and Salem, (2010).

In this reference, it was concluded the importance of the geotechnical investigations, which recorded a score of 4.73 with MAD of 0.39. Accordingly, authors recommended to perform an intensive soil investigations and increase the number of boreholes to have the opportunity to study the soil conditions in better way.

2.11.4 Favorable Soil Conditions

Generally, each type of soil presents positive and negative effects with respect to productivity (Hegab and Salem,(2010), according to the survey participants which were asked to rank soil conditions on tunneling operations for identifying the most favorable one. Table (12) shows the survey results. Sand was stated to be the most favorable soil media for the tunneling process, followed by Silt and Clay, while Boulders and Backfill were found to be the worst ones.

Table 12 - Favorable Soil Conditions with respect to Microtunneling (Hegab and Salem, (2010).

Soil condition	Score	Absolute deviation
Sand	4.09	0.95
Silt	3.41	0.90
Silty clay	3.09	0.67
Hard clay	3.05	1.14
Soft clay	3.05	0.55
Backfill	2.00	0.76
Boulders	1.81	0.94

73

The productivity of tunneling operations also depends on several factors with most of them being interdependent (Hegab and Salem,(2010), Moreover, a profitability key issue is to study and analyze all contributing factors, especially the soil condition which is the most influential one.

2.11.5 Tunneling Machine Cutter Head Discs

In this thesis, cutter head disc replacement intervals have been studied and recorded at several locations across Qatar for an attempt to correlate the effect of various rock layers on these intervals. Thus, a literature survey for rock properties related to cutting disc wearing is presented in this section. Generally, the relative percentage of minerals indifferent Moh's hardness classes (>7, 6-7, 4-5 and <4) can be utilized to determine the cutter life. Additionally, microscopic petrographic analysis is considered as the most widely used tool for determining the hardness of coarse-grained rocks and soils. Furthermore, X-ray diffraction (XRD) complementary with differential thermal analysis (DTA) is also a well-known tool for fine-grained rock and soil. Generally, the higher the percentage of hard mineral elements in the soil/rock, the more abrasive the soil/rock and the shorter machine cutter head life.

2.11.5.1   Rock Abrasion Test Methods

According to Ozdemir and Nilsen, (1999) and Büchi et al., (1995), the most commonly used methods for obtaining the abrasiveness are:

1)   The Vickers test, giving the Vickers Hardness Number - VHN,

2)   The Cerchar test, giving the Cerchar Abrasivity Index - CAI,

3)   The LCPC abrasimeter test, giving the LCPC abrasivity index - ABR, and

4)   The NTNU abrasion test, giving the Abrasion Value - AV/AVS.

The above methods usually provide a fair and reliable value of the abrasiveness, but collecting the required representative samples is their main issue. A brief explanation of each method follows:

1) The Vickers Test

A vickers hardness number is provided by defining the micro-indentation hardness of a mineral. The definition of this number is the ratio of the load applied to the indentor (gram or kilogram force) divided by the contact area of the impression (mm2), this identor is a square based

diamond pyramid with a 130° included angle between opposite faces, so that a perfect indentation is seen as a square with equal diagonals. Similar to the Moh's hardness, the VHN is used for a preliminary estimation of the abrasivity and the expected cutter wear.

2) The Cerchar Test

The Cerchar Abrasivity Index (CAI), as shown in figure (16), is calculated by scratching a freshly broken rock surface with a sharp pin of heat-treated alloy steel, with the Cerchar Abrasivity Index (CAI) calculated as the average diameter of the abraded tip of the steel pin in tenths of mm after 10mm of travel across the rock surface. This test presents the advantage of application in irregular rock samples. Usually, the CAI value ranges from 0.5 for soft rock (such as limestone and shale) to more than 5.0 for hard rocks (such as quartzite) (NILSER et al., 2006). The following table (13) shows CAI classes for rock classification.
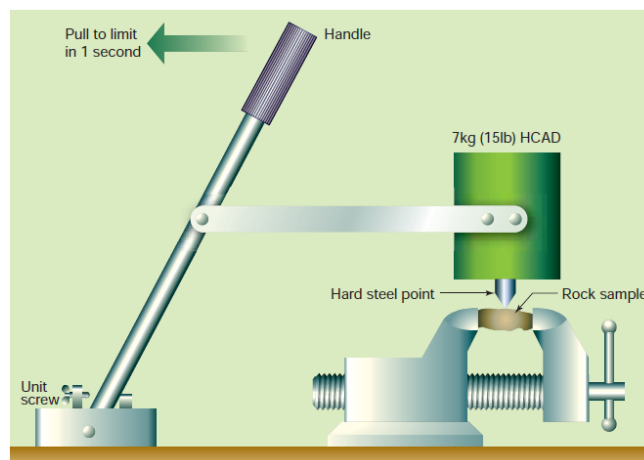
Figure 16 - Cerchar Abrasion Test (NILSER et al., 2006).

Mean CAI	Classification
0.1–0.4	Extremely low
0.5–0.9	Very low
1.0–1.9	Low
2.0–2.9	Medium
3.0–3.9	High
4.0–4.9	Very high
≥ 5	Extremely high

Table 13 - CAI Cerchar abrasivty index classification result, (Cerchar, 1986).

3) The LCPC Abrasimeter Test

In this test, rock or soil samples are tested using the 4mm-6.3mm fraction, crushing process is done for the Coarse grained material and sieved, fine grained material (<4 mm) is not included in the test, then an air dried sample is placed into a cylindrical drum, and a rectangle steel propeller is rotated at a speed reaches 4500 rpm, the propeller is a relatively soft steel, that can be scratched with a knife easily, then ABR (Abrasion Coefficient) corresponds to the weight loss of the propeller per ton of the tested sample. This test is commonly used for rock samples. Reliable correlations are performed between the LCPC test, Cerchar test and the UCS of the rock tested (NILSER et al., 2006).

4) The NTNU Abrasion Test

Engineering Geology Laboratory of the Norwegian Institute of Technology (NTH) in the early 1960's developed a methodology for estimating the rocks drillabilty (Lien, 1961). Abrasion testing of crushed rock particles <1mm, as shown in figure (17), was then presented together with the Brittleness test and the Sievers-J miniature drill test for determine the drillability parameters DRI (Drilling rate index) and BWI (Bit Wear Index). Moreover, starting from year 1980, according to the method developed by the NTH/NTNU Department of Building and Construction Engineering (in 1996, as result of a merger, NTH changed name to NTNU - the Norwegian University of Science and Technology - and the Norwegian method now is referred

to as the NTNU method), the tests have been performed for predicting TBM wear behavior mainly, (Bruland et al., 1995). Regarding TBM cutter head wear prediction, a test piece of cutter steel is used instead of the tungsten carbide test piece used for percussive drilling estimation, and the parameter CLI (cutter life index) is calculated instead of BWI (NILSER et al., 2006).
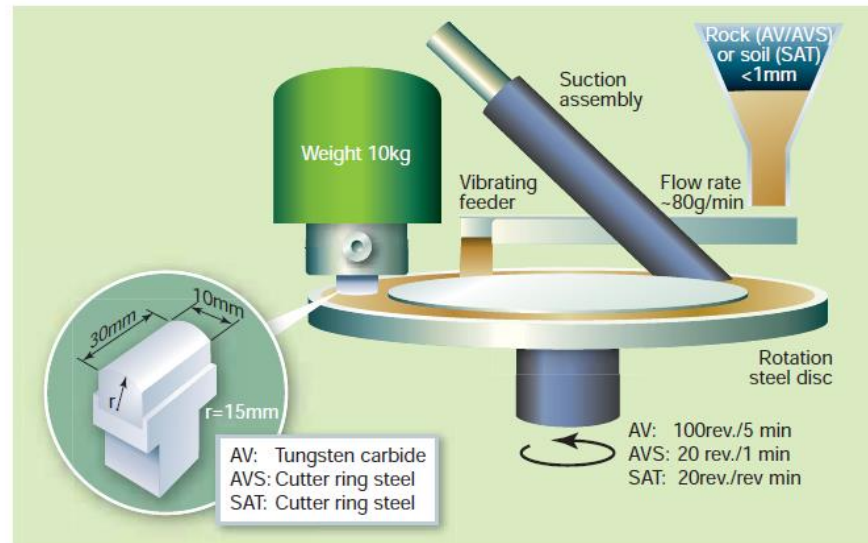
Figure 17 - NTNU Abrasion Test (NILSER et al., 2006).

2.11.5.2   Impact of Rock Abrasion

Yarali and et al., (2008) stated that during tunneling projects, economic pressure and a waste of budget can be found in cases of false rock abrasion estimations, that cause excessive usage of the cutting tools. Cerchar abrasion test is considered as a simple and quick test to estimate abrasiveness using the Cerchar Abrasiveness Index (CAI). Due to this simple and applicable to small-size rock samples method, the Cerchar test is highly used (Plinninger and Restner, 2008). Test guidelines were firstly described in France 1980 (Suana and Peters 1982), with several future works studying the impact of physical, mechanical and geological rock properties on the abrasion percentage (Plinninger and Restner, 2008).

Rock abrasiveness can be linked to the presence of abrasive minerals like quartz, since quartz is considered as one of the important parameters of abrasivity (West, 1989). Moreover, rock's strength influence is lower than quartz's petrographic parameter (Yaral, 2005),since rocks with high strength may have low quartz content (Schimazek and Knat 1970).However, relevant works

indicate that rock's strength value and abrasivity affect the CAI value (Deliormanlı, 2012, Al-Ameen and Waller, 1994).

Calculations based on single and multiple regression analyses can estimate the CAI value of sandstones (Moradizadeh, M., Ghafoori, M., Lashkaripour, G. and Tarigh Azali, S.,(2013) Linear regression fitting is adequate for estimating the percentage of quartz in a rock, while w% which is a physical feature of sandstones, has the least value of R2 with the adjusted R2 not appropriate for determining CAI. It was also revealed that the percentage of cement and grain rocks do not affect the value of CAI according to the conducted multiple regression. In contrast, point load test results are good criterions for estimating CAI in sandstones.

Lester M. Bradshaw presented a research in order to discuss whether the microtunneling in hard rock is fact or fiction. This research based on Bradshaw's fifty years of experience of tunneling through full and mixed face metamorphic and sedimentary rock formations existed at the eastern of United States.

Bradshaw stated that Microtunneling has been going on since the 1990s, and all sizes of MTBMs (Micro Tunneling Boring Machines) have recorded successful performance in sedimentary rock formations, since the author believed that sedimentary rock behavior is similar to the dense soils with a usual high productivity. Bradshaw mentioned that only very hard abrasive sandstones can be considered as a challenging case for the microtunneling in sedimentary rocks, in these cases, the drive length can be limited for the cutting tools wearing action, which may be solved by replacing the cutting discs through the face access. In the late 1990s and early 2000s, poor results were recorded during several contractors' attempts to microtunnel in igneous and metamorphic rock formations according to Bradshaw, since the rock was hard and abrasive that caused rapid damage and wear to the used cutting discs before the completion of the drives. At that time, Micro-tunneling Boring Machines (MTBMs) was not designed to allow face access during the excavation to replace the cutting discs, moreover, Bradshaw believed that the involved contractors often did not have an expert tunneling engineer who can understand both tunneling machine limitations and the obtained geotechnical information that may ease the rock cutting, due to this, the result was a series of valiant attempts to produce similar production rates achieved in soft ground through hard rock formations. In the early 2000s, there was a revolution in the tunneling industry, since the German company Herrenknecht introduced its T series of

MTBMs that have "face access", this series allow the tunneling contractors for the first time to enter the MTBM cutter head to replace the defected cutter head discs and continue the drive instead of digging a rescue shaft over the tunneling machine or pulling back the MTBM to the jacking shaft. Despite the safety concerns about the process of face entrance specially in mixed face conditions under the water table, but these series of machines have been safely performed, and they showed a govern economic role regarding the success of microtunneling in full face hard abrasive rocks. Author stated that the T-series are relatively heavy with greater cutting torque compared to the same sizes of microtunneling soft ground machines, which allow them to tunnel through harder rock formations. However, Bradshaw revealed that although the difficulty of entering the 59.25" OD tunneling machines which have size of the face access only 18" ID that will make the working space in the cutter head chamber very narrow, but the possibility of entering the cutter head deserves this risk.

Bradshaw believed that the ability to excavate through hard abrasive rock using MTBMs smaller than 59.25" that have no face access is still fiction than fact, due to the usage of small cutting tools that cannot impose enough pressure to cut such hard rock layers, also, the small amount of metal in the cutting discs that may wear away quickly, which is very common to occur in the perimeter gage disc cutter specially, which make it very risky to use the MTBM with no face access through these hard formations.

The author in this research mentioned that microtunneling machines face serious physical limitations through the hard abrasive rock even with the face access, despite the increase of torque and weight but they are still 'MICRO", since they use small cutting tools which are capable of only 17000 +/- pounds of thrust, while the larger tunneling machines reach 70000 pounds of thrust, that show the huge difference in the rock cutting ability. According to Bradshaw, these limitations cannot be specified by a simple measurement such as the upper limit of unconfined compressive strength (UCS), but too many other factors are involved such as: rock fracturing, hardness, abrasiveness, mineralogy, MTBM size, power, thrust, torque, and cutter head design.

It is worth to mention that Bradshaw started rock micro-tunneling in 2004 using a Herrenknecht face access MTBM, Bradshaw has completed thirty drives totaling over 14,000' in predominantly hard abrasive metamorphic rock, with machines diameter range from 36" to 77"

OD, and rock unconfined compressive strength (UCS) ranged from 500 to 43,500 psi and abrasivity from Cerchar 1.0 to 5.5.

Bradshaw recommended a full understand of both the geology of the project and the limitations of microtunneling method, equipment and materials. This understanding can be achieved through an intensive study of the geotechnical investigations to obtain the following:

- Type of rock by drive and within drive length,

- Location of any transition zones from rock to soil creating mixed face or mixed reach drives,

- Orientation & spacing of rock fractures/bedding,

- Unconfined Compressive Strength (UCS) with description of structural or non-structural failure of every test,

- Cerchar abrasivity Index,

- RQD (%), Recovery (%),

- Brazilian Tensile Strength,

- Point Load Test,

- Punch Penetration Test,

- Thin Section Petrographic Analysis including description of any mineral suturing conditions, and

- Historical research into previous TBM tunnels in the area that may have encountered rock suturing or other "tough rock" mining conditions such as amphibolite or diabase.

Based on rock microtunneling experience, Bradshaw introduced the following observations and recommendations:

1) MTBM Advance Rate – A simple formula for calculating rock TBM mining rates per shift. This formula involves instantaneous penetration rate per revolution, cutter head revolutions per minute, and mining hours per shift. Since the conventional hard rock Tunneling Boring Machines (TBM) have 10-18 rpm while the MTBMs cutter heads turn 2.5-5 rpm with lower thrust capacity compared to the TBMs, therefore, microtunneling in hard rock gets slower penetration rates compared to the larger tunneling machines, and this difference in rates increases as the rock gets harder.

2) Cutting Gage – Perimeter gage disc cutters excavate the tunnel opening, which is called "overcut". This function is performed by few cutting discs turned nearly perpendicular to the direction of the tunnel, due to this function, these discs are subjected to notably greater wear from abrasion than the other disc cutters. In some cases this wear action increases too much that causes MTBM to be obstructed by its own shell. This serious issue oblige the microtunnel drive to be short enough or the MTBM must allow face access to replace the cutting discs in order to complete the drive successfully. Also Bradshaw recommended the overcut selection to be left up to the contractor, from the author experience, the overcut is set to be 25% to 50% greater than in soft ground microtunneling to allow the gage cutters to wear down and not obstruct the MTBM. However, the overcut is not recommended to be so large as to limit the MTBMs ability to develop articulation steering reactions.

3) Cam Locking and Pipe Wedging - Cam locking usually creates point loading from an object trapped in the overcut void. Wedging involves slurry cuttings passing under the MTBM cutter head, this action results to lift the MTBM and pipe string towards the roof of the tunnel. These actions can occur frequently during a rock microtunnel drive and will lead jacking forces to spike by 50% to 100%.

Smith (1997)proposed that rock hardness is usually affected by the mineral composition, especially quartz, which is considered to be abrasive mineral thatreaches level 7 in Moh's hardness scale. Materials that contain high quartz percentage can be classified as hard and abrasive rocks difficult to disassemble.
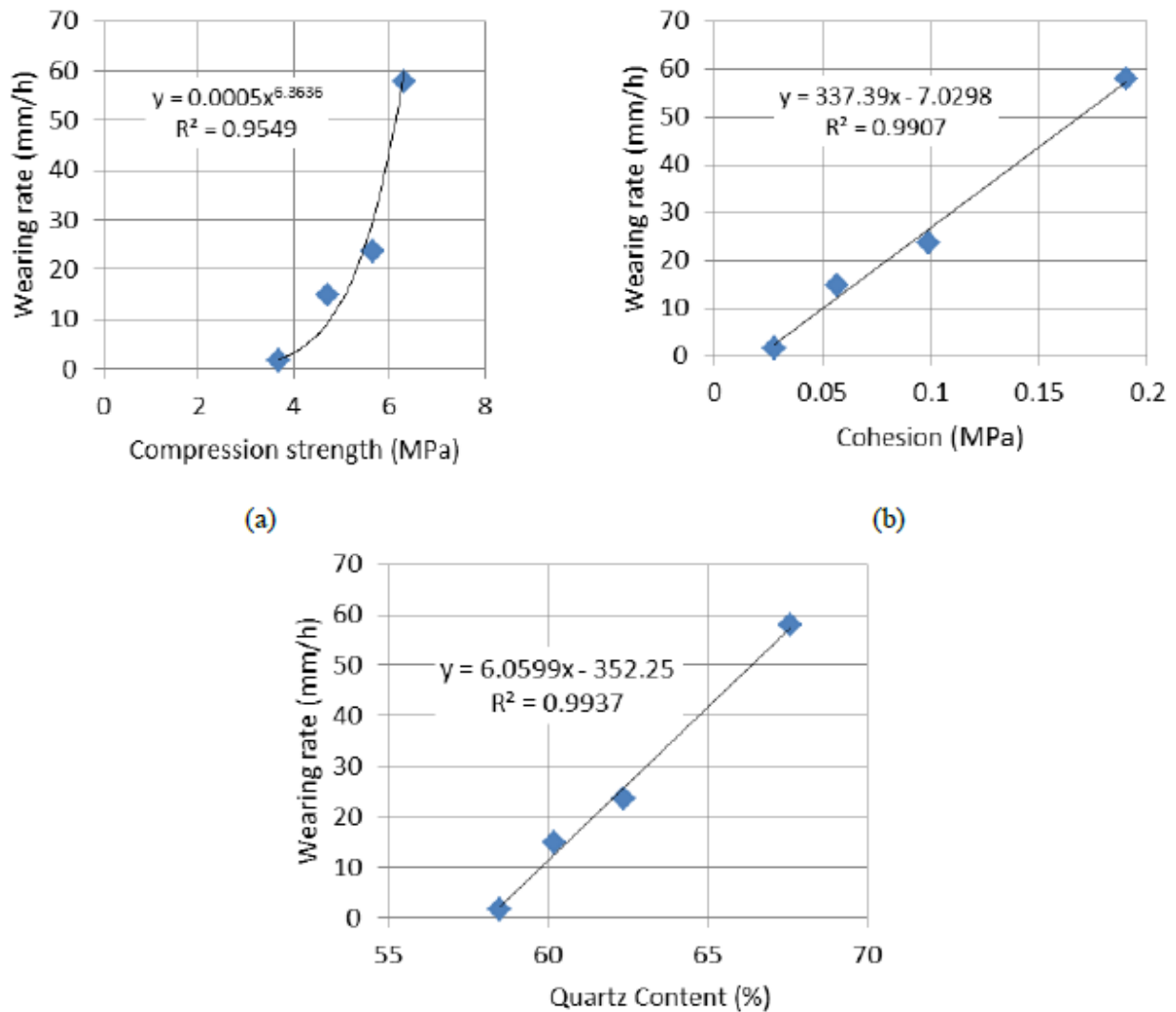
Figure 18 - Effects of (a) compressive strength; (b) cohesion and (c) quartz content on the wearing rate of ripping tip, (Smith, 1997).

Smith presented correlations between the wearing rate of a ripper breaker and the corresponding rock parameters, in order to study the effects of compressive strength, cohesion and quartz content on the wearing rates. He proved that the quartz effect on wearing rates is very significant and can be approximated by a linear function. However, when comparing the quartz content effect with cohesion on the wearing rates, the cohesion effect is negligible. It was also observed that the compression strength effect is initially limited but becomes significant when wearing rates exceeds 30% and can be approximated by a power equation as shown in figure (18).

2.12. Excavation Technique

2.12.1 General

A literature survey for the excavation process is presented in this section, since an attempt to relate Qatar's rock properties and recorded productivities was desired. Generally, digging, ripping and blasting are excavation methods for overburden materials in open pit mines based on the excavated material's characteristics. Usually, ripping is the preferred method for cost reasons, although its main and common issue is the ripper wearing that can significantly affect the productivity ratio. Assessments on materials' ripping ability have been performed based on compressive strength (Weaver, 1975, Kirsten, 1982, Smith, 1986, Singh et al., 1987, Karpuz, 1990, Kramadibrata, 1998), weathering degree and spacing of discontinuities (Pettifer and Fookes, 1994), as well as seismic velocity (Catterpillar, 2008). Based on the assessments, the ripping method is preferred for compressive strengths of 10 to 25 MPa, while blasting method is selected in cases of compressive strengths above 25 MPa (Bieniawski, 1989). Other parameters can be also added to the compressive strength which affect the excavation productivity, Karpuz (1990) and Kirsten (1982)indicated that cohesiveness should be considered when determining rock mass rippability along with quartz content (hardness).

Apparently, correct earthmoving productivity estimation has confused several researchers for many years (Smith, 1997), since no accurate and adequate prediction model existed. Smith proposed a model for examining the excavator/dump truck earthmoving system that considered the truck's loading cycle, the truck's haulage to disposal area, the material deposition, and the haul return in queue for repeating the process. This operation is considered to be a complex one since numerous factors are involved and affect the output rates. Furthermore, some of these factors are not determinable with their importance not clear as indicated by Christian and Xie (1996), who performed a North America survey with contractors, revealing significant variations in opinions about the importance of each factor.

Christian and Xie (1996) listed the factors that were considered to affect earthmoving output table (14) and their determinability. The table reflects the U.K. earthmoving industry and common U.K. geotechnical conditions.

Factor (1)	Determinability (2)
Haul road soil parameters	Medium
Haul road gradient	High
Haul road rolling resistance	Low
Haul road length	Medium
Plant specifications	High
Plant operator ability	Low
Load area characteristics	Medium
Type and location of obstructions	Low
Weather	Very low
Material susceptibility to weather	Low
Load cycle times	Medium
Truck maneuver times	Medium
Truck travel speeds	Medium
Dump times	Medium
Loader bucket volume	High
Bucket passes per load	Medium

Table 14 - Factors Influencing Earthmoving System (Christian and Xie, 1996).

Smith (1997) believed that the main governing factors in earthmoving productivity are the excavator/loader, with, Gransberg (1996) indicating them as ''the critical characteristics of the loading facility which ultimately impact on the overall system production''. Thus, by changing the excavator (prime mover) features and by increasing the number of working teams may lead to a notable increase in earthmoving productivity.

Rosihan Pebrianto (2014) presented a study on the factors affecting the ripping productivity at open pit mining at Bangko Barat, South Sumatra, Indonesia.

In this study, the excavation process was conducted using a Caterpillar D9R bulldozer ripper with a long penetration tip, This research mainly studies two approaches: firstly the laboratory characterization of rock mass such as the compressive rock strength, cohesiveness, and quartz content, and secondly field observations on the wearing action occurred in ripper tip and ripping productivity. Four common types of overburden materials were selected including sandstone, tuffaceous sandstone, silty claystone, and silty sandstone.

Aksoy (2008) stated that a selection of proper excavation machine can affect the production rate significantly and as a result, studying the geomechanical and geotechnical properties of the rock mass can facilitate the excavator selection.

Chapter Three:Research Approach

Figure (19) shows the various steps that this research passes through to arrive at conclusions. A geological research was performed studying the rocks of the Arabian Peninsula and specifically the rocks across the Qatar peninsula, in order to acquire a full understanding of the soil formations and the past geological conditions that caused the existing formations. This study reveals the presence of rock layers in the majority of Qatar soil map. Thus, a classification system was exploited to classify the existed rocks accurately. The Rock Mass Rating (RMR) system proposed by Bieniawski (1989) was chosen and used as the classification tool during this research. Although there are several similar rock mass classification systems in the literature, such as the Q system, the Rock Structure Rating System (RSR), and the Geological Strength Index (GSI). The RMR system was chosen as the most appropriate scheme, since it suits the natural rock conditions of Qatar. Moreover, RMR classification system becomes a mandatory request for the majority of the owners, consultants and contractors who participate in any project in Qatar nowadays, also, the complexity of the rocks formations in Qatar needs to utilize a smooth and easy access system to ease the process of classifying the existed rocks, bearing in mind the accurate and expressive results obtained in this classification system compared to other systems, these considerations were the govern reasons of choosing this system to be the classification tool in the research. In addition to this, tunneling and excavation productivity rates were collected from different projects (38 tunneling projects, and 22 excavation projects) in different locations across Qatar in order to have valid and reliable evaluation between the RMR grades in these locations and the corresponding production rates recorded during these projects, to reach the main purpose of the research which is; to establish a full and real geotechnical classification matrix using suitable and common classification system (RMR) and the corresponding productivity rates for two of the most important construction activities in Qatar, which are excavation and tunneling. The overall research framework was comprised of the following steps.
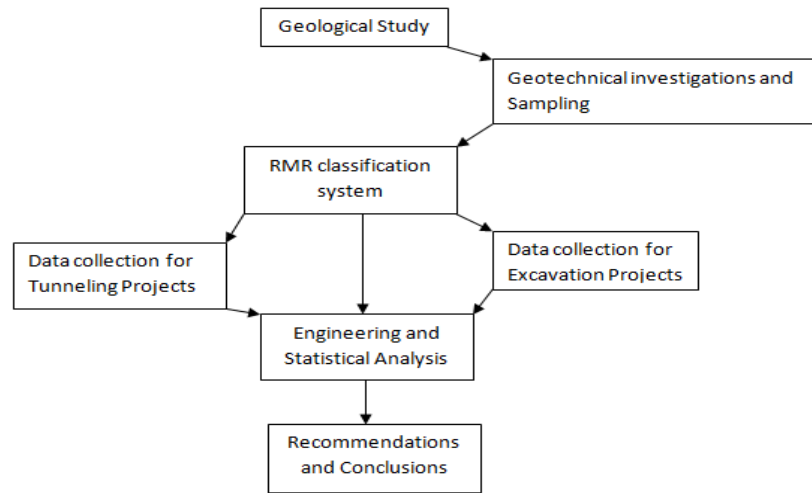
Figure 19 - Research Steps Flow chart.

3.1   Geological Study

In order to acquire a deep understanding of the soil nature and the geotechnical challenges in Qatar, it was crucial to conduct a precise geological research and analysis. A literature survey was initially performed concerning Qatar's geology. The history of the existed rocks and their formations behavior and properties are the required key features in order to establish a solid research base which will integrate both the in-site practical challenges with the scientific geological facts and theories. The data collected during the performed geological studies along the different regions of Qatar, provided a better understanding of the different soil formations, layers and characteristics of rocks in the State of Qatar, as discussed in the previous literature review section.

During this study, several meetings were held together with one of the most trusted soil analysis labs operating in Qatar, namely the Qatar Engineering Lab (QEL), for discussing the nature of the rocks across Qatar and for sharing their geotechnical background experience. Based on this feedback, the Qatar's rock map was divided into five main zones according to the rock qualities and characteristics of each zone, at maximum depths of 30m which is also the maximum operational depth for most of the construction or infrastructure activity in the region. These zones will be discussed thoroughly in the next Data Analysis Chapter.

3.2   Sampling and Soil Investigations

An extended number of soil investigation reports from several projects across Qatar was collected and studied in this stage. On the contrary, only few samples were bored and tested under the researcher supervision due to the high cost of these tests and other difficulties that author faced. As a result, some laboratory tests for a single project (in Massaied Area) were performed with the presence of the researcher. The assessments included unconfined compressive strength (UCS) ASTM No. D 7012, and point load tests ASTM No. D 5731. Despite the limited number of tests, the collected soil investigation reports were very substantial and adequate to provide the researcher the necessary properties of the existed rocks, since there ports reveal complete rock geotechnical information such as,

- The exact location of these samples,

- Boring logs that contain (the rock descriptions, rock names, weathering state, RQD%, FI, depths, ground water table level and SPTs),

- Coring photos,

- UCS (unconfined compressive strength) test results,

- Point load test results,

- Brazilian tensile strength test results,

- All the geotechnical tests (field and lab tests) that were conducted on rocks, and

- Coring methods and coring conditions.

It is worth mentioning that QEL lab has put a huge effort in providing these reports, knowing that projects names are kept confidential, as QEL labs are considered one of the most trusted geotechnical labs in Qatar.

During this study, one or two borehole samples were taken for each project in order to efficiently represent the rock properties of the sampling locations. The borehole locations were chosen after studying all the boring logs and after understanding the rock formations and types of the

respective locations, in order to perform accurate and representative boreholes for each project which is required by the classification stage.

3.3 RMR Classification System and Implementation

After the soil zone categorization, the next necessary step was to choose a rock classification system for assisting the following phases of the research framework. A random classification system selection without a previous full understanding of the geology and characteristics of rocks in Qatar, would be a misleading step for the research achievements.

Having a standard rock classification system is very important not only for developing a scientific understanding of the rocks and geological nature of Qatar, but also for assisting the different bidding, design and execution stages of all the mega construction projects taking place in the state of Qatar.

The Rock Mass Rating (RMR) classification system was used for classifying the collected boring samples and is based on the several geotechnical information of the soil investigation reports. The system's output is an RMR figure that describes the rock quality and is going to be explained deeply in the next chapter. The geotechnical data used in this system includes;

- UCS results,

- Point load test results,

- RQD%,

- Ground water table conditions,

- Weathering State, and

- Discontinuities conditions.

Each parameter of the above factors gives a number and their summation represents the RMR number which reflects the rock quality grade as shown in table (8) earlier in this research.

Three tools were used to get the RMR number for each rock coring. The first is the tables that were proposed by Bieniawski (1989) tables (8), and are considered the most common tool to interpret the RMR grade. The second tool is an online free tool that can be found at www.mining.com. A print screen caption for this tool is shown in figure (20). This tool is considered an easy to access tool that allows its user to familiarize with the classification system.

The third tool is some graphs presented by Erik Eberhardt- UBC Geological Engineering, these presentations were taken from the course "Geotechnical Engineering Practice" which is part of the 4th year geological engineering course at the University of British Colombia (Vancouver, Canada). A comparison table between the results obtained by these three different tools will be illustrated in the next chapter.

Figure 20 - Online tool for calculating RMR rock grades
(http://www.edumine.com/xtoolkit/xmlicon/rmr.htm).

A classification system modification was performed by the researcher due to the small variance between the RMR numbers of the borings which could lead to difficulties in interpreting the rock quality results. More precisely, it may become very hard to identify the difference between the rock boring samples despite their significant difference in quality. Thus, new classes were added

to the classification system in order to achieve better and sharper judgment of the rock boring sample quality. The modified rating table is shown in table (15).

Table 15 - Modified RMR rating classification system.

Rating	100 <-- 81	80 <--71	70 <-- 61	60<--51	50 <-- 41	40 <-- 31	30 <-- 21	<20
Class No.	VIII	VII	VI	V	IV	III	II	I
Description	Very Good Rock	Good Rock	Fair to Good Rock	Fair Rock	Poor to Fair Rock	Poor Rock	Very Poor to Poor Rock	Very Poor Rock

As a result,a combined sheet was prepared containing all the sampling locations in Qatar and their corresponding rock properties along with RMR numbers and grades in order to provide a full overview of the variety of the results found in Qatar.

3.4 Construction Projects - Excavation and Tunneling - Data Collection

Claimed Data was collected from different projects across the state of Qatar, some of them are completed while the others are still in progress. These projects are executed by different contractors. Each project data was collected in parallel with getting the soil investigation reports in order to achieve the purpose of this research. As a result, 36 projects of the studied ones are tunneling projects while 22 projects were related to excavation activities in Qatar.

This stage of the research revealed many challenges and obstacles, since the researcher tried to study sufficient number of projects for establishing the best evaluation conditions along the processes of tunneling and excavation projects together with rock classification for allowing a strong analyzing stage. One of the obstacles that the researcher faced was the process of entering in any on-going project, since the high safety regulations followed in Qatar demand several visitor requirements before project site clearance. In addition, some project's high confidentiality added extra burden during the data collection stage, as some of the visited sites were under a direct consultancy of the Authority of Public Works (Ashghal) which asked for several approval letters before disseminating any information regarding the project's soil reports and productivity rates. As a result of that, the stage of data collection was time consuming mainly for getting the required approvals before accessing the necessary data.

Furthermore, two questionnaires for the excavation and tunneling projects, respectively, were prepared for being filled during the projects visits. Several meetings were appointed with the contractor's representatives, an action that was strongly encouraged since talks with contractors and planning engineers was necessary to reach a real and accurate description of their daily work sequences at the visited projects. It is well known that the contractors are the most involved persons carrying out the actual construction actions and are responsible for all the related technical incidents that may occur during the execution of the excavation and tunneling activities, especially with incidents dealing with the various qualities of the existed rocks. Appendix -B depict a copy of the two questionnaires needed to be filled during the visits. Few modifications were made in the tunneling questionnaire in order to adapt the different tunneling techniques which differ from the excavation ones. The questionnaire includes the three following sections;

- **Section A**: Includes the respondent name, title and years of experience in that kind of projects. The researcher was asked by the respondent to keep this section information secret.

- **Section B**: Includes the project name, location, scope of work, expected date of completion and % of finished works (to make sure that contractors data is based on recent and updated recordings). Few data of this section was allowed to be published such as the project location and % of finished works (in some projects only).

- **Section C**: Includes the average productivity, equipment used, problems faced the contractor caused by the existed rocks, technical data related to each technique (excavation and tunneling) such as average depth, excavation method, work sequences and average working hours (for the excavation projects), machine diameter, cutting head type, cutting discs replacement rates, average tunnel depth, and average working hours (for the tunneling projects).

Finally, a sheet was prepared, including all the above collected data in order to form a table with all projects' locations, existing rock layers, RMR grades, the corresponding claimed actual productivity with the used equipment and all the related technical details that may be used in the data analysis stage.

3.5 Data Analysis

The main objectives of this research stage were two. For the first objective, the necessary categorized rock map of the state of Qatar in five zones according to the rock qualities and characteristics was initially prepared by the researcher. Next, the study of the RMR grade results collected along the numerous Qatar locations was performed. During this study, the concept of developing a novel Qatar rock map combining RMR grades of a certain depth in a single one became the main goal. For this reason, the selected studied depth ranged from 10m to 20m, since it is considered as the main interest depth for the majority of the construction and infrastructure projects in Qatar. After the selection, an attempt to export the map was performed and will be explained in details in the next chapter.

The second objective of this stage was the evaluation of the projects' production rates and all their related technical data obtained from the 2 questionnaires. This study will provide useful results and figures that can facilitate future processes dealing with similar qualities of rocks and can be valuable for owners, contractors and consultants during bidding, design and execution phases. Thus, a statistical analysis was performed using the SPSS software powered by IBM, in order to get accurate, clear and quantitative analysis of the obtained data. Moreover, several tables were prepared for illustrating and highlighting the collected results from a practical engineering perspective.

In this stage, two factors for each activity were identified as the governing factors that mainly contribute in the research analyzing process which are;

- Excavation Works:

- Productivity rates for each location, and

- Capacity of the jack hammers used in the process.

Since most of the excavation processes that take place in Qatar prefer the jack hammers ripping method for the excavating method, it was decided to study the capacity of these jack hammers in productivity. In such way, we add an engineering value to the research by covering an important technical issue and by providing the ability to compare various rock qualities with the production rates evaluating the capacity of the used equipment for expressive and logic results.

- Tunneling Works:

- Productivity rates for each location, and

- Cutting discs replacement rates.

It is worth to mention that despite the numerous factors that affect the tunneling operation as described in several papers (Hegab and Salem, 2010), the researcher has chosen to concentrate on the productivity rates and the cutting discs replacement rates. According to Hegab and Salem (2010), the soil condition factor is ranked in the first place of the factors affecting the productivity of the tunneling operations, and due to this, it was important to discuss and record the productivity of these operations during the penetration of different rock qualities existing in Qatar. However, the reasons of choosing the cutting discs replacement rate are as follows;

a) The relatively high compressive strength of the rocks at several locations across Qatar,

b) The important contribution of the cutting discs in the tunneling operation,

c) The abrasion that hit the cutting discs during the tunneling process,

d) The high cost of these discs that must be considered by the contractors in the bidding phase, and

e) Recommendations given by the tunneling experts through the research questionnaire, where it was identified as a common issue here in Qatar.

All the results and outputs of these stage will be shown and explained in details in the next chapter.

Chapter Four: Data Analysis

4.1   General Qatar Rock Map

During this phase, a general guide map for the rocks in Qatar was created based on past geotechnical expert's experience with the rocks in Qatar. The map was divided into five main zones according to the rocks' strength, for average depths of 30 meters, since this depth is considered the most critical for the geotechnical engineers in Qatar.

As shown in the map of figure (21), five main zones form the general overview of the rocks in Qatar, and can be characterized as follows;
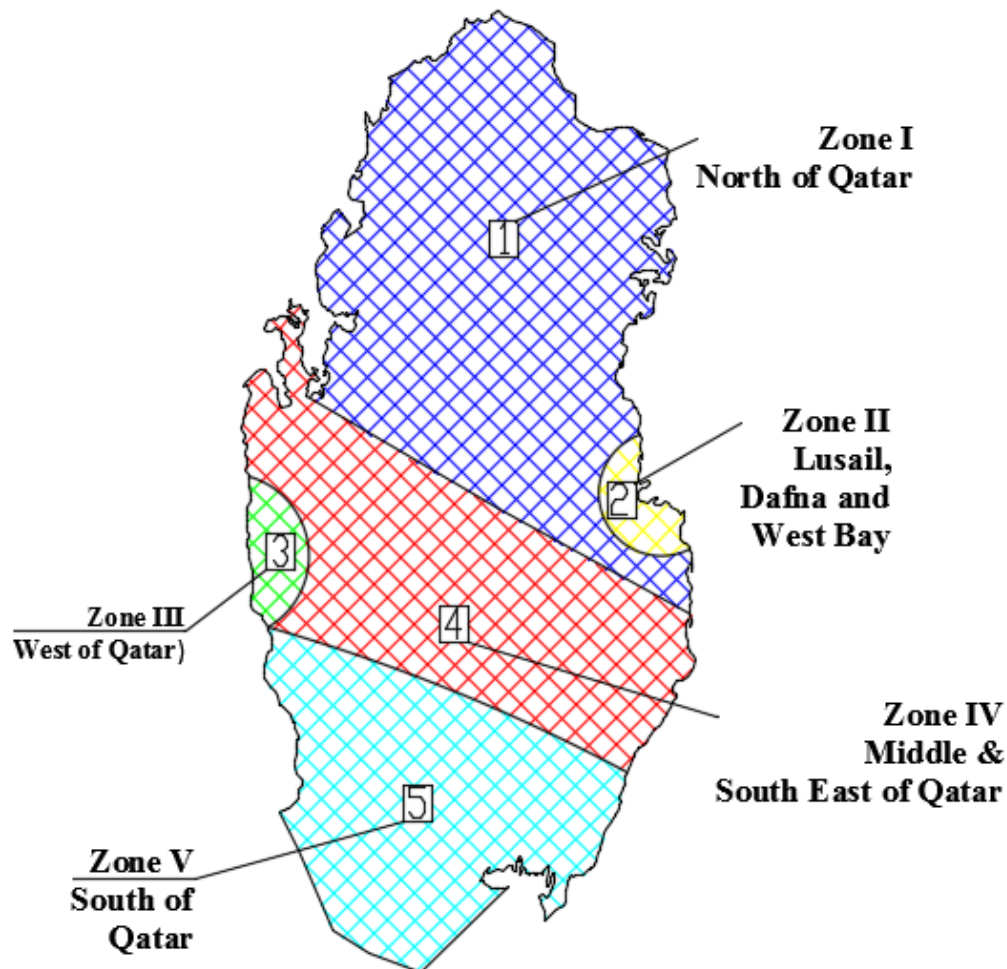
Figure 21 - General Qatar rock map.

- Zone I   North of Qatar

This zone contains several types of rock layers such as Simsima limestone, Midra Shale and Rus formations which can be found also throughout the whole country. However, a common feature that merges all these layers in one zone is the relative high compressive strength, making this part of Qatar a challenging location for construction applications especially at Al Khor area. Moreover, numerous cavities exist in this part of the country that may affect any civil applications.

- Zone II   Lusail, Dafna and West Bay

 A large layer of sand constitutes the major component of the soil in this zone, which is out of the scope of this research. A highly weathered Simsima limestone also exists, forming the majority of the rocks in this location, with few other locations containing medium weathered Simsima limestone with large pockets of secondary cohesive materials (attapulgite clays). Generally, this part contains rock layers ranging from Very Weak to Weak rocks.

- Zone III   West of Qatar

Layers of reddish clay are the major elements of the soil in this part. Despite the absence of urban life in this area, few borings were conducted, showing the existence of these clay layers.

-Zone IV   Middle & South East of Qatar

This zone introduces a relatively medium strong rock layer, excluding Al Rayyan and Al Wakrah areas that are famous for their toughness. The middle zone of Qatar is known for moderate values of compressive strength where the Simsima limestone and Midra shale form the rock layers with the presence of interbedded organic materials.

- Zone V   South of Qatar

Similarly to Zone I, this zone contains relatively high values of compressive strength but with different properties. A 2cm sand covers most of the soil at this part, making it a unique feature of this zone, while large areas contain Sabkhas in their surface. Simsima limestone and few layers of Midra shale characterize the majority of the Moderate strong to Strong rock layers in this part.

4.2 RMR Classification System

4.2.1 How it works

The Bieniawski's Geo-mechanics Classification System (1976, 1989), generally referred as the Rock Mass Rating or RMR system, provides the means for a quantitatively classification of the rock mass quality. The calculated RMR values can range from 0 to 100and are based upon five universal parameters:

- Strength of rock,

- Drill core quality (RQD),

- Groundwater condition,

- Joint and fracture spacing, and

- Joint characteristics.

A sixth parameter, the joint orientation, is applied differently only in specific applications such as tunneling, mining and foundations.

This classification system implies a general rock mass quality without a specific correlation to other construction or design requirements, although it can be correlated to mass properties such as the stand-up time. The values determined for each parameter are aggregated to determine the final RMR value. The rock mass quality is then classified using several classification parameters as shown in table (7) earlier in this research.

For any sample data, the parameters, values and ratings can be generally described as:

- Strength of intact rock: Ratings range from 0 to 15.

- RQD: 0 to 100 percent. Ratings range from 3 to 20.

- Spacing of joints: Range from less than 0.1 to over 2 m. Ratings range from 5 to 20.

- Condition of joints: From silken-sided with separation more than 5 mm to very rough surface with no separation. Ratings range from 0 to 30.

- Ground water inflow: Rating range 0 to 15.

- Adjustment for orientation: Orientation of discontinuities is used to adjust the summed rating according to whether discontinuities are adverse relative to the engineering project. Rating range 0 to -50.

Each of these listed variables can introduce a noticeable effect in the overall RMR. A key indicator in the rock mass quality is the drill core RQD, which is a general measure for the amount of fracturing in a rock mass (explained earlier in this study). Some assumptions were made to characterize the rock in addition to the descriptive notations in the rock coring logs. The made assumptions include:

- RQD% is equal to the RQD% value for each core run.

- Rock UCS is based on the UCS values obtained from laboratory testing.

- Joint spacing was considered based on the   reported fracture index values, the   RQD%, and the engineering judgment.

4.2.2   RMR Calculations

As mentioned earlier in this research, one of the main factors that encouraged the author to classify the obtained samples using the RMR classification system was the related complexity of the rock formations in Qatar which requires a smooth and easily accessible system for simplifying the process of rock classification with accurate and expressive results.

For obtaining the RMR grades of the tested samples, three tools were used, as described earlier in the research approach chapter. These tools are the following:

1. Tables proposed by Bieniawski's (1976, 1989).

2. An online free tool that can be found online at www.mining.com.

3. Graphs presented by Erik Eberhardt- UBC Geological Engineering.

Consequently, a result comparison sheet based on these three tools was prepared to justify their appropriateness. Results obtained through the first and the second tool were proved exactly similar, while results using the third tool were found to be higher, as shown in the following

figure (22). This is mainly due to the different utilized methods for obtaining the RMR ratings for the weathering state and joint conditions between the third tool and the other two tools.
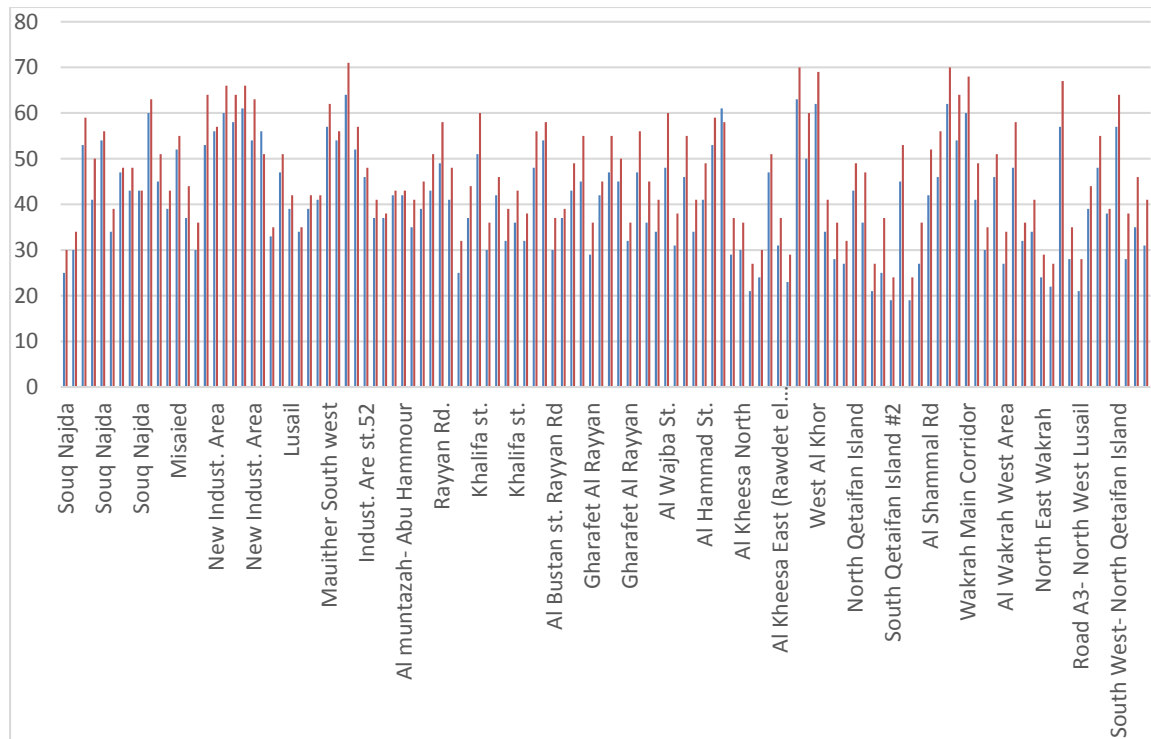
Figure 22 - Bar Chart comparing RMR obtained from Bieniawski's tables and Erik Eberhardt-UBC Geological Engineering

More preciously, close viewing of these results to determine the variance can be recognized by studying sixteen cases as shown in the following figure (23).
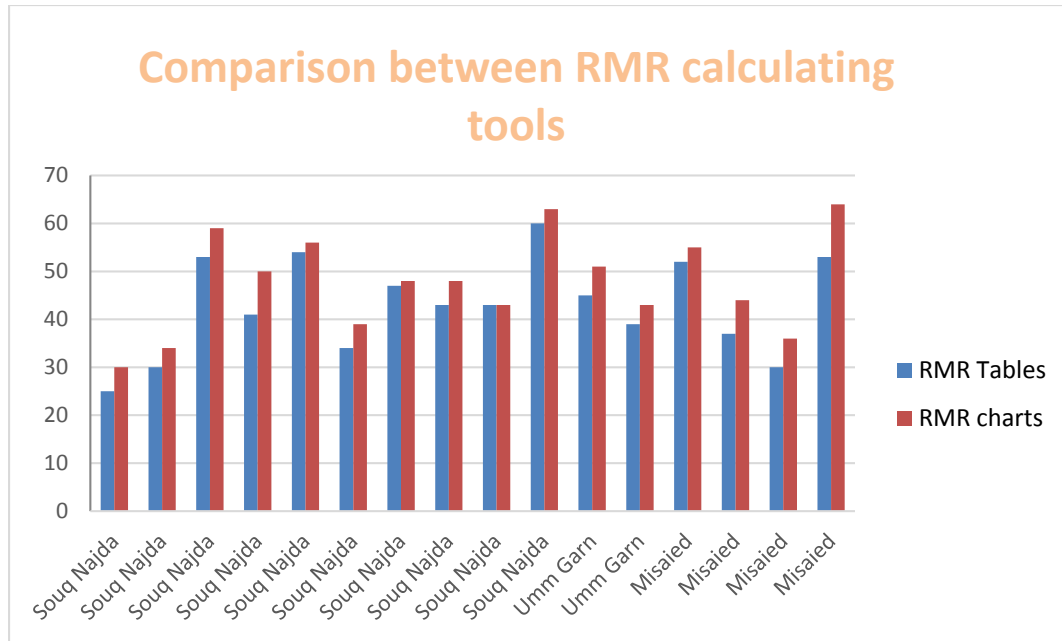
Figure 23 - 16 cases of results obtained by RMR Bieniawski's tables and Erik Eberhardt- UBC Geological Engineering.

4.2.3   RMR Evaluation

Obviously, the RMR classification system has been proved over the time to be a useful classification system for the rock mass, and it is characterized by its smoothness, expressiveness and relatively easiness of usage, despite some definition inaccuracies. Hence, it has to be noted that the degree of fracturing and the condition of those fractures contribute to the 70% of the Rock Mass Rating, and also that there is a high level of double counting between two factors, namely the RQD% and the joint spacing. Moreover, there is also an inconsistency in the case when a rock with RQD of 90–100% is allocated with the full 20 points while a rock with a joint spacing of 60–200mm is allocated only 8 out of 20 points.

Generally, the RMR is used (as is RQD by itself) to correlate with rock mass parameters, including the rock mass strength and deformability, thus, it is considered as an easy to access, expressive and simple classification system so far (Hoek, 1980).

Due to the small variance between the RMR numbers of the obtained borings which might lead to inaccuracies when interpreting the rock quality results as mentioned earlier, the researcher has modified the RMR classes, in order to achieve a better and sharper judgment of the rock boring sample quality. The modified rating is shown in table (15) at the research approach chapter.

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4.3   Qatar Rock Map according to RMR grades

The aim of developing a novel Qatar rock map combining RMR grades of a certain depth in one single map has become one of the research targets. For this reason, a depth ranged from 10m to 20m was selected, as this depth range gathers the most interest throughout the majority of the studied construction and infrastructure projects. After the selection, an attempt to export the map was performed and is shown in the following figure (24).

Project Name	Rock Layer	Average RMR Value	Rock Grade
Souq Najda	Simsima Limestone	48	Poor to Fair Rock
Maisaed	Simsima Limestone	35	Poor Rock
Lusail	Simsima Limestone	34	Poor Rock
Mauthier South west Doha	Midra Shale	54	Fair Rock
Mauthier South west Doha	Simsima Limestone	61	Fair to Good Rock
Industrial Area St.53	Simsima Limestone	37	Poor Rock
Al Muntazah - Abu Hamour (south-west Doha)	Simsima Limestone	37	Poor Rock
Al Muntazah - Abu Hamour (south-west Doha)	Midra Shale	42	Poor to Fair Rock
Rayyan Rd.	Simsima Limestone	38	Poor Rock
Rayyan Rd.	Midra Shale	40	Poor Rock
Khalifa St.	Simsima Limestone	39	Poor Rock
Khalifa St.	Rus Formation	30	Very Poor to Poor Rock
Al Bustan St. Rayan	Simsima Limestone	48	Poor to Fair Rock
Al Bustan St. Rayan	Midra Shale	30	Very Poor to Poor Rock
Gharafet Al Rayyan	Simsima Limestone	45	Poor to Fair Rock
Gharafet Al Rayyan	Midra Shale	45	Poor to Fair Rock
Al Wajba St.	Simsima Limestone	42	Poor to Fair Rock
Al Wajba St.	Midra Shale	34	Poor Rock
Al Innabi St.	Simsima Limestone	39	Poor Rock
Al Innabi St.	Midra Shale	34	Poor Rock
Al Salam St.	Simsima Limestone	53	Fair Rock
Al Kheesa North	Rus Formation	23	Very Poor to Poor Rock
Al Kheesa East (Rawdet el Hammam)	Rus Formation	26	Very Poor to Poor Rock
Al Birka (North East Qatar)	Rus Formation	50	Poor to Fair Rock
West Al Khor	Rus Formation	34	Poor Rock
North Qetaifan Island	Simsima Limestone	43	Poor to Fair Rock
South Qetaifan Island #2	Rus Formation	21	Very Poor to Poor Rock
South Qetaifan Island #3	Midra Shale	25	Very Poor to Poor Rock
South Qetaifan Island #2	Simsima Limestone	19	Very Poor Rock
South Qetaifan Island #3	Simsima Limestone	45	Poor to Fair Rock
Al Rayyan Al Gaded	Simsima Limestone	19	Very Poor Rock
Abu Nakhla (west Maissed)	Simsima Limestone	50	Poor to Fair Rock
Wakrah Main Corridor	Simsima Limestone	44	Poor to Fair Rock
Al Wakrah West Area	Simsima Limestone	48	Poor to Fair Rock
North East Wakrah	Simsima Limestone	27	Very Poor to Poor Rock
Road A3- North West Lusail	Rus Formation	25	Very Poor to Poor Rock
South West- North Qetaifan Island	Simsima Limestone	43	Poor to Fair Rock

Figure 24 - RMR grades for different locations across Qatar at depths range (10-20m).

In this map, all the studied projects during the different stages of the research were considered, and more precisely, all the project locations (represented by the boreholes chosen previously) were marked in the map in order to illustrate the calculated RMR values. The average values of RMR were calculated for all the similar rock layers existed in each location at the studied depths. Afterwards, data was exported to define the required map which aims to provide geotechnical engineers a reliable reference map of the rocks in Qatar based on the RMR grades. Through this map, engineers will have the ability to predict the rock properties in certain project locations and

can more easily facilitate the processes of planning, bidding and executing in various civil engineering projects.

Moreover, a detailed map for each studied location clarifying the existed rock layers and their assessment according to the RMR classification system are attached in Appendix -A.

4.4 RMR Results Analysis

4.4.1 Overview of the Rock Layers Existed at the Studied Locations

As mentioned previously, the collected soil investigation reports were analyzed and classified using the RMR classification system. Thirty eight projects across the state of Qatar were studied, and geotechnical parameters were evaluated and combined in one table for defining reliable relations between the RMR values of the existed rock layers and the geotechnical parameters, bearing in mind that several boreholes per project were selected to represent each project's parameters. Three rock layers which were found at the studied locations are worth to be mentioned;

- **Simsima limestone (SL)**

Simsima Limestone was generally observed as Weak to Strong, light grey to off white, fine grained limestone/dolomitic limestone. The limestone was found to be fresh to slightly weathered, occasionally highly weathered, calcareous, with presence of few to some voids of up to 90 mm and occasional of few to some pockets of stiff to hard, light-greenish-grey, occasionally motted pink silt/clay, occasional patches of Chert, occasional few nodules of crystalline gypsum and occasional bands of Very Weak to Weak, light-greenish-grey calcareous siltstone/calcisiltite. Joints were observed to have dips varying from 5 to 90°, and to be very closely to widely spaced, undulating, rough to slightly rough, clean, tight to moderately wide. Occasional non-intact core sections were recovered as fine to coarse gravel of Very Weak to Weak limestone/dolomitic limestone, with occasional presence of silt matrix. It is important to mention that some layers of Simsima limestone, especially at higher levels, were found to be highly weathered affecting the average RMR grades for the Simsima limestone. However, these highly weathered layers can be described as Very Weak to Weak, light-brownish-grey, fine-grained dolomitic limestone, highly weathered, calcareous, with a presence of occasional few voids and few to some pockets of stiff, light-greenish-grey silt/clay, mostly washed off during drilling.

- **Midra Shale MSH**

Midra Shale layers generally consists of Weak, thickly laminated, brown, fine-grained siltstone interbedded with Weak to Medium-strong, off-white, fine-grained limestone, fresh, calcareous,

with presence of occasional voids of up to 60 mm, few nodules, veins and bands of crystalline gypsum, few pockets of hard, light-greenish-grey silt/clay and occasional patches of chert. Joints are generally observed to have dips of 5 to 40°, and to be closely to widely spaced, planar, undulating, smooth and rough, clean, tight, open and moderately wide. Due to the bi-modal nature of the MSH, it can be divided in two types, the MSH Siltstone (MSHS), and the MSH Limestone (MSHL). Because of the limited thickness of this layer, the majority of the discussion in this research considers the MSH as a combination of both types.

- **Rus Formation RUS**

Rus generally consists of Weak, off white, fine grained limestone, fresh to occasionally slightly to highly weathered, calcareous, with presence of occasional voids of up to 20 mm, occasional patches of chert, occasional nodules and veins of gypsum, interbedded with Weak, light-brown siltstone/calcisiltite and Very Weak to Weak, light-greenish-brown calcilutite.

4.4.2 Rock Layers Parameters Comparison

Two main geotechnical parameters were studied in depth, the RQD% (Rock Quality Designation) and the UCS (unconfined compressive strength test) ASTM No. (D 7012-2010) results. These two parameters were chosen to be studied thoroughly, since they are considered as highly expressive parameters not only for the RMR classification system, but also for the general rock quality descriptions. During this study, table (16) was introduced containing the maximum and minimum as well as the average values of the RQD% and UCS results based on the results of the three existed rock layers. Through this table, it was noticed that Simsima limestone layers are presenting high values of RQD% and UCS values. In contrast, the result combination of Simsima limestone layers with the highly weathered Simsima limestone layers decreased the average values of the Simsima limestone, since the highly weathered layers are presenting low values of RQD% and occasionally low values of UCS as well. However, dividing them into two layers might be not accurate, since both of them present similar geological formations and they are found in an entangled formation widely across Qatar, making such a separation irrational which might cause also misleading results.

RQD%			
Layer Name	Maximum	Minimum	Average
Simsima Limestone (SL)	100	8	60
Midra Shale (MSH)	90	20	61
Rus Formation (RUS)	90	10	33
UCS values MPa			
Layer Name	Maximum	Minimum	Average
Simsima Limestone (SL)	153	1.78	37.04
Midra Shale (MSH)	41.7	3.6	22.53
Rus Formation (RUS)	42.41	2.06	12.56

Table 16 - RQD% and UCS recorded values for the three main rock layers in Qatar.

In addition, Midra Shale layers have recorded the highest RQD% values, since the grade of compaction becomes higher with the depth increase (Midra Shale layers are overlaying by Simsima limestone layers) and the percentage of cohesive materials found in Midra Shale increase the RQD% of these layers. Furthermore, Midra Shale layers are having moderate UCS values, due to the presence of Moderate to Strong limestone, siltstone and occasional mudstone. In contrast, Rus formation layers are exposing the lowest average values of RQD% and average compressive strength values, since the high strength of the limestone, siltstone and mudstone, forming the Simsima limestone and Midra Shale layers, is quite effective compared to the soft limestone in the Rus formation layers and the distinctly weathering state of the Rus formations layers.

Subsequently, the recorded RMR values were studied for each layer, and it was found that the Simsima limestone layers exhibit the highest average value of (42), while Midra shale layers were averaged at (38) and Rus formation layers were calculated to have an average value of (29). These values are in compliance with the RQD% and UCS results, since Simsima limestone layers were expected to record the best rock layer state, exceeding the Midra Shale layers and Rus Formation layers. Despite the higher RQD% average value of Midra Shale compared to Simsima limestone, the RMR values are not affected due to the slight variance between RQD% average values in both layers, and also due to the other rock properties which contribute to the

RMR grades and reveal the better rock quality for Simsima compared to Midra Shale. Table (17) shows the RMR values for each layer.

Layer Name	Maximum	Minimum	Average
Simsima Limestone (SL)	64	19	42
Midra Shale (MSH)	54	25	38
Rus Formation (RF)	50	21	29

Table 17 - Average RMR values for the three main rock layers.

Based on the table results, a histogram graph was plotted in figure (25) for all the RMR values,in order to have a clear overview of the recorded values across Qatar, ranging from 19 (at Al Rayyan Al Gadded area) to 64 (at Mauither south west area), with an average value of 40 for the studied location. This graph reveals also that the studied rock layers in Qatar ranged from poor rock to good rock, with the average grade being of fair rock, for all the studied samples.
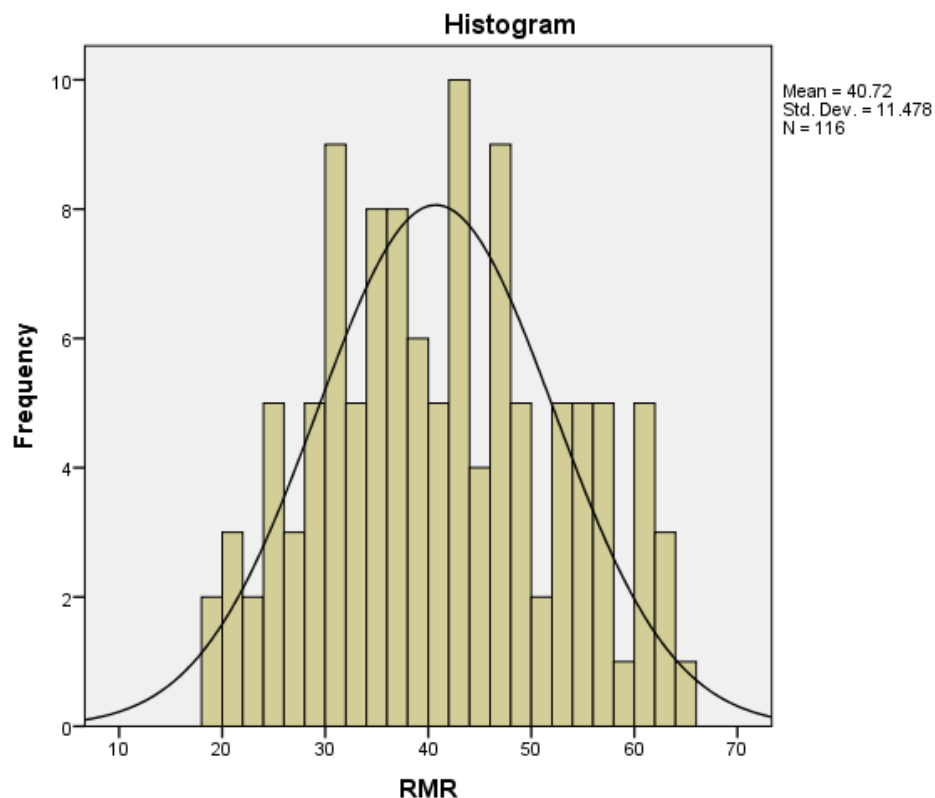
Figure 25 - Histogram chart for the RMR grades across Qatar.

4.4.3 RMR Values Relationships

During this study, the author has tried to identify the correlation between the two main geotechnical parameters (RQD%, and UCS values) and the corresponding RMR values obtained in all the studied locations. In order to establish an easy and reliable tool for interpreting the RMR values from these two parameters, and identify such potential correlations, the two graphs of figures (26) and (27) were plotted for achieving these aims.
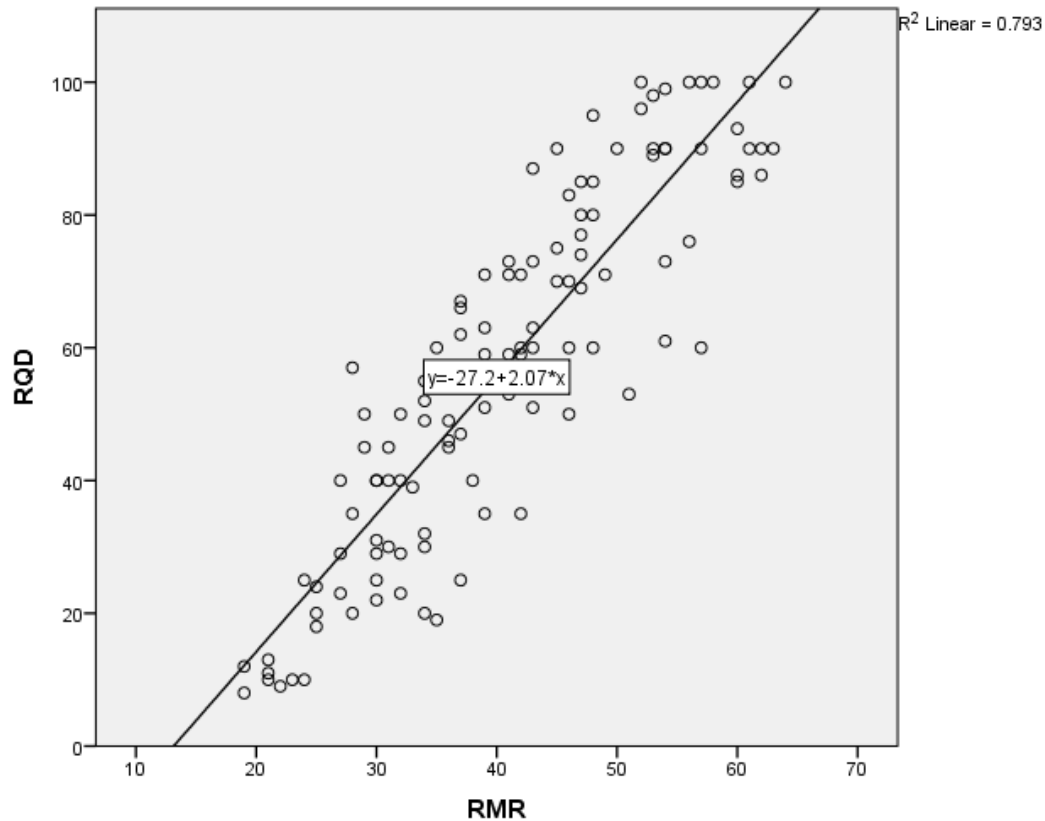
Figure 26 - RMR grades Vs. RQD%.

In figure (26), the linear relation between the values of both axes reveal how the RQD% values significantly affect the RMR values. At confidence level of 95%, the significant F-value equals to 3.49E-33 and P-value of 1.75E-28, which indicates the high statistical significance of the relation between the two parameters. This relation has an upper and lower bounds equations; {y = 21.597 + 0.41x} for the upper range, and {y = 16.83 + 0.33x} for the lower range. This confirms the findings of Steve Hencher (2013), where the RMR is used to express RQD to correlate with rock mass parameters, including rock mass strength and deformability. As a result,

this graph can be considered a reliable tool for interpreting the expected average RMR grade for any rock sample in Qatar providing its RQD% value, by utilizing this graph and intersecting the line that represents the relationship equation between the RQD% and RMR grades, the expected average RMR for this sample can be identified.
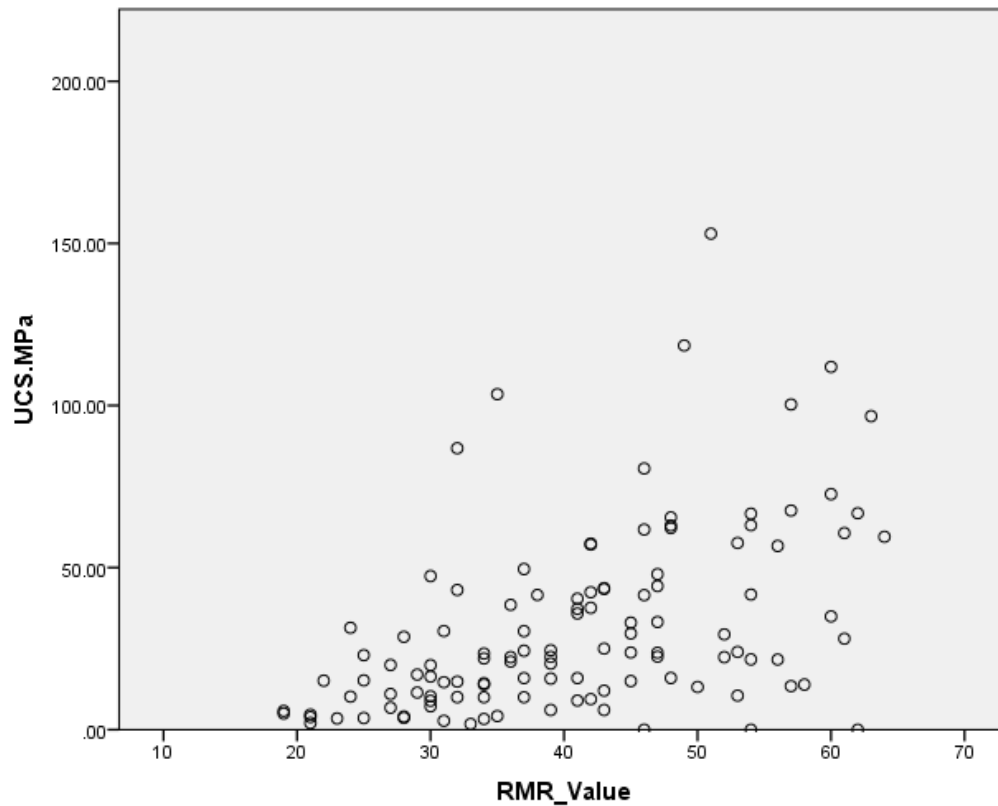
Figure 27 - UCS values Vs. RMR values.

For graph (27), an unstable relation was observed between the values of the two axes, which clarify the small contribution of the non-intact rock strength to the corresponding RMR values. This can be considered as one of the drawbacks of the RMR classification system, since the large class of UCS values (50-100 MPa) of the same rating in the RMR grade leads to neglect the variance of strength values. To fully understand the relation between the compressive strength values and the corresponding RMR grades, the bar chart of figure (28) is presented to illustrate the large variance existing in the results of RMR values for slight differences in the compressive strength results.
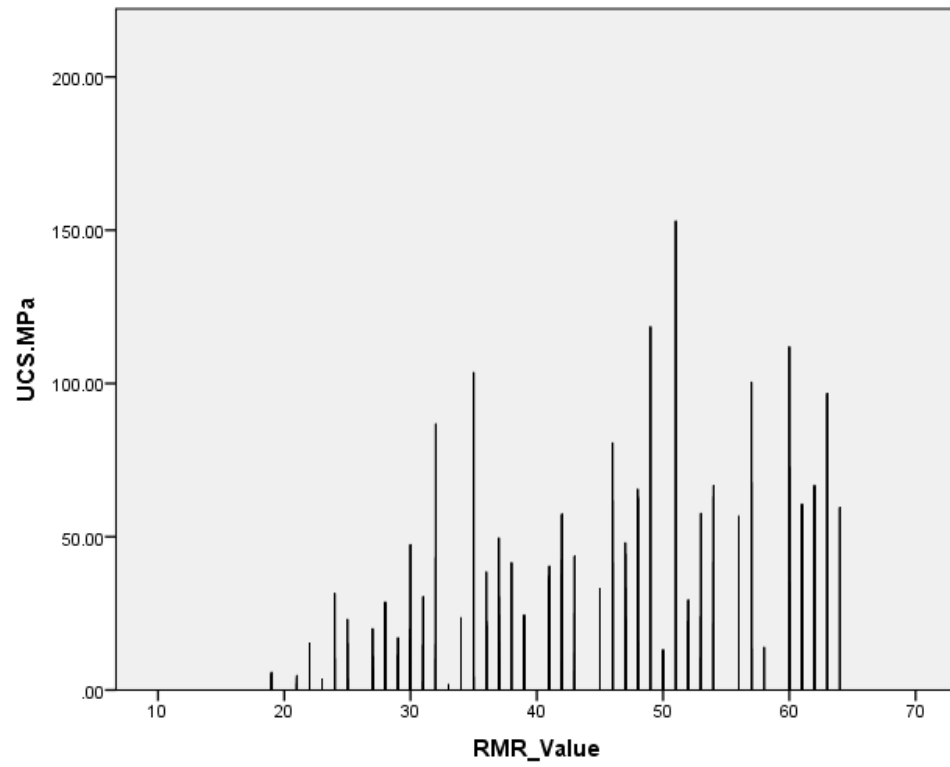
Figure 28 - Bar chart for the RMR values and the corresponding UCS values.

4.5   Data Analysis: Tunneling

4.5.1   Productivities and RMR Values Relationship for Small Tunneling Machines

In this stage, data from 36 different projects across Qatar was collected after the questionnaires discussed earlier were filled during the sites visits, representing a total number of thirty six soil investigation reports and their corresponding productivities and cutting discs replacement intervals for the tunneling projects in Qatar. As it was mentioned earlier, the current classification process was performed for the soil investigations reports (for the tunneling and other projects) in order to acquire a full knowledge of the geotechnical parameters and to be able to calculate the RMR grades for all the studied locations. Thus, in this stage of research, the recorded productivities and the cutting discs replacement intervals from these projects have been studied and analyzed in order to get useful, expressive and reliable relationships between these data and the rock layer geotechnical parameters of these locations. It is important to mention that due to the differences in the hydraulic systems, the various sequences of work and their associated fittings of small and large diameters for the tunneling machines, the productivities and all the other aspects related to the work progress are affected. In order to reach a constructive assessment of the rock layers in Qatar and their impact to the production rates, the author has separated the recorded data of each project into projects with tunneling machines smaller than 1500 mm, and into projects with tunneling machines larger than 1500 mm, since each project group can be considered as a single class due to the slight and acceptable variance in the mentioned operating aspects. Another factor that must be stated is the daily production rates which were recorded for 10 working hours, as it is the common working practice in the state of Qatar.

Figure (29) shows the relation between RMR grades and their corresponding productivities for tunneling machines of less than 1500 mm.
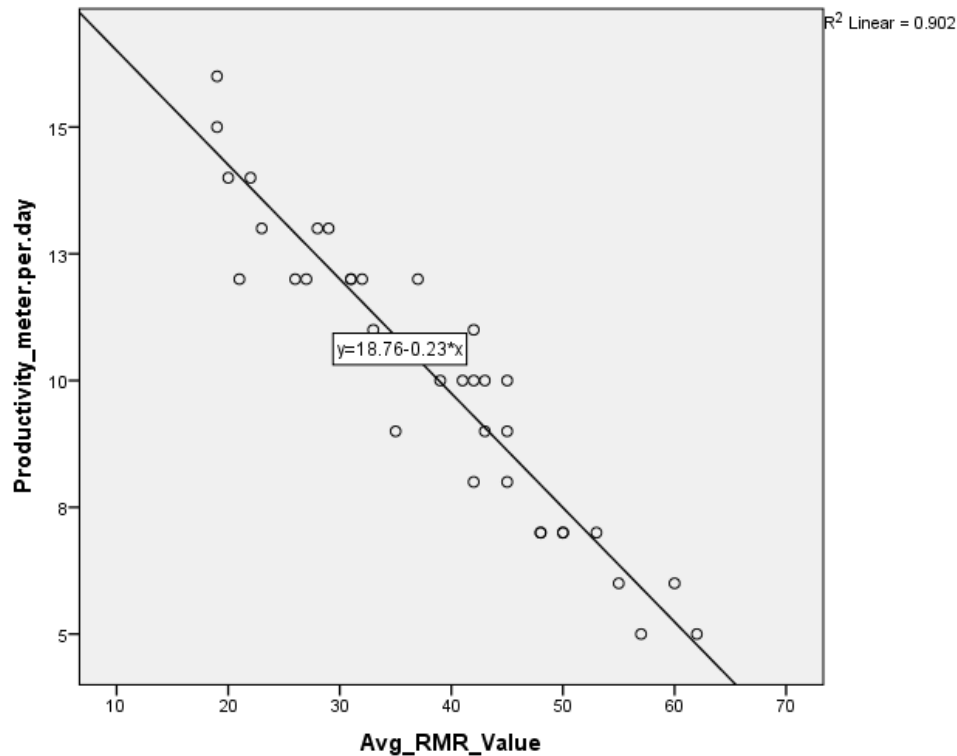
Figure 29 - RMR values Vs. Productivities M\day for tunneling machines <1500 mm.

The RMR grades at this graph represent the rock layers that existed at certain depths where the tunneling machines operated and were recorded. In this relation, the regression gives a significant F-value of 5.18E-18 and P-value of 1.58E-26 for the intercept, which indicates the high significance of the relation between the two parameters statistically. This relation has an upper range equation of $\{y = 83.69 - 3.5x\}$, and a lower range equation of $\{y = 73.76 - 4.45x\}$ at confidence level of 95%. As a result, this relation can be expressive for predicting the average tunneling productivities in Qatar, especially when comparing these outputs to the results obtained during the attempts of correlating the RQD% values with the tunneling productivities, which gives significant F-value of 6.39E-13 that reflects low statistically significant results, with low R squared value and large lower and upper margins of values. These results indicate that RMR classification system is reliable and expressive tool for predicting the average tunneling productivities.

In figure (29), the highest rate of production was recorded at Al Rayyan Al Gadded area with 16 m\day, while the lowest rate was observed at two locations; Abu Nakhla (west Maissaied) and New Industrial area with both at 5 m\day, respectively. The presence of multiple rock layers at

the excavated depths significantly affects the productivity rate, however, it is quite difficult to clarify the exact length of each layer at the designed route of the tunnel. Despite that, it was observed that change of the recorded productivities (increasing/decreasing) in the presence of more than one layer at several locations. For example, the presence of the Midra Shale layers at Al Rayyan Road area together with the Simsima limestone layers have decreased the average recorded productivities compared to the similar recorded data of RMR grade of Simsima layers which existed solely for both the small and large machine sizes at different locations. Another example was observed at Khalifa Street area, where the existence of Rus formations layers side by side with Simsima limestone layers has increased the average productivities, recorded at this area, compared to other Simsima layers with similar RMR grade. The reason of this disturbance is that each layer at the excavated depth contributes with its properties to form the new combined layer that will be excavated by the machine. Due to this, the effect of the Midra Shale layers decrease the production rates significantly, since they contain large pockets of cohesive materials (clay) with high plasticity and cohesion features, combined with Moderate to Very Strong limestone and siltstone, which form a non-favorable excavating media for the tunneling machines especially for tunneling machines with rock cutting heads which usage are mandatory for the rock layers existed in Qatar. Similarly, the presence of Rus formations side by side with the Simsima limestone layer increases slightly the production rates, due to the nature of the Rus formation layers which contain Very Weak to Weak soft limestone and form a more favorable weak rock excavating media, which consequently, increase the productivities at these locations when compared to locations having Simsima limestone layers with similar RMR grades.

The productivity Vs. RMR grade graph for smaller tunneling machines shows three different behaviors along the different RMR values. The line starts with a sharp certain slope for low RMR grades, while it tends to be linear at the medium RMR grades, then finally it shows a quick tendency towards zero for the high RMR values. This behavior shows that productivities are largely affected by the high RMR values which may become a serious issue for the engineers dealing with that kind of rocks.

4.5.2 Financial Evaluation

Based on these findings, another factor has been included in the graph which is the cost\m', in order to fully understand the influence of the RMR grades on the tunneling machine

productivities. As a result of this, the average direct cost of the tunneling process has been calculated in order to reach an average process cost per day. The following costs were included in the overall cost calculation:

1. Machine (whole set including separation unit {Herrenknecht A.G. company}, pumps, hoses, cables and diesel) rental fees: 8000 QR/day,

2. Crane rental fees: for the machine less than 1500 mm, 50 tons crane will be sufficient 40000 QR/month,

3. Labors: for machines less than 1500 mm, 1 operator +1 Forman + 3 labors are sufficient, 34000 QR/month,

4. Generator: 300 KVA generator is adequate for these diameters, 7000 QR/month, and

5. Materials: including fresh water for excavating and plain concrete for the thrust wall and launching eye, 15000 QR/month.

An average cost of 336000 QR/ month is estimated for the tunneling process which gives a value of 11200 QR for the total cost per day for 30 working days per month. This cost has been divided by the average recorded production rate per day in order to have an estimation of the exact per meter cost for each RMR grade existed at the studied locations. The following graph of figure (30) shows these results.
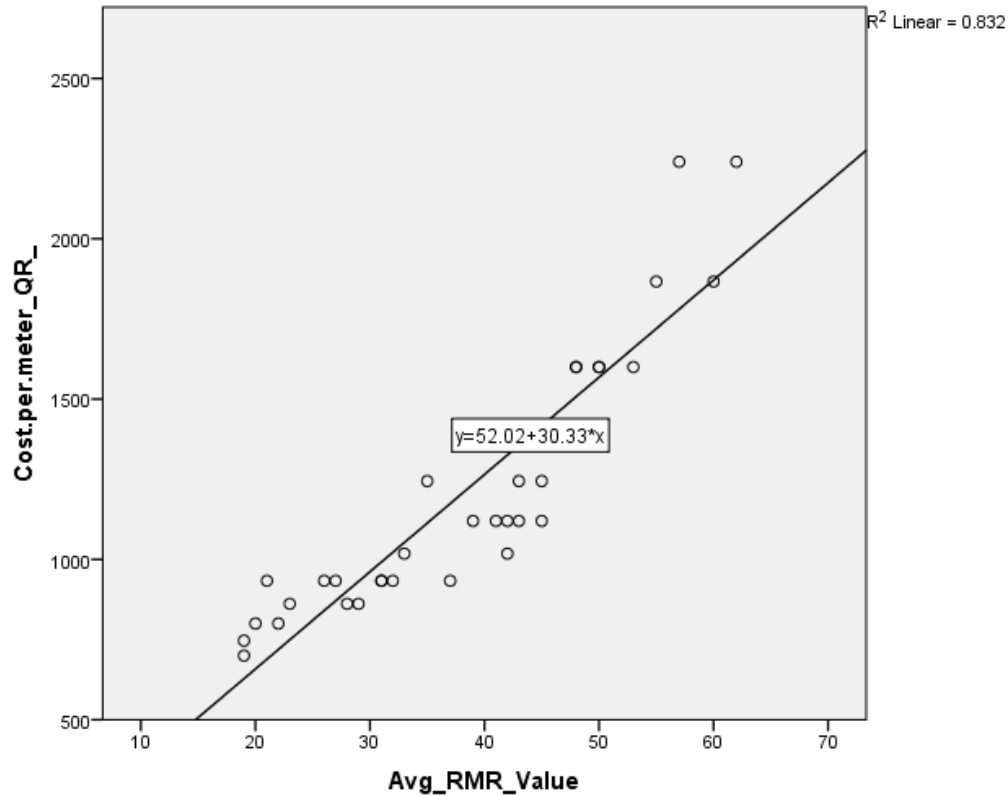
Figure 30 - Average RMR values Vs. Cost per meter (Qatari Riyals) for AVN machines <1500 mm.

This figure shows the significant variation regarding the tunneling meter cost for a location exhibiting a low RMR grade (RMR: 19 - Cost/m: 700 QR) and other locations with high RMR grade (RMR: 62 - Cost/m': 2240). These costs dramatically affect the engineering decisions (owners, designers and contractors) especially when dealing with rocks that present high RMR values. In order to reach a full insight of the RMR values effects and the resulted productivities in the cost per meter scale, another graph in figure (31) is plotted to illustrate this great influence that must be taken of main concern by all the decision makers.

Figure 31 - Average RMR grades Vs. Average Productivity M\Day Vs. Cost per meter (Qatari Riyals) for Tunneling machines < 1500 mm.

This figure shows the significant effect of the RMR grades on both productivity and cost, which strongly highlights the notable importance of the RMR classification system to predict the productivity which leads to better cost estimation process for the tunneling process.

4.5.3 Productivities and RMR Values Relationship for Large Tunneling Machines

Similarly, the relationship between RMR grades at operated depths and their corresponding recorded productivities for tunneling machines with diameters more than 1500 mm has been studied and discussed. Figure (32) shows the graph combining these two parameters.
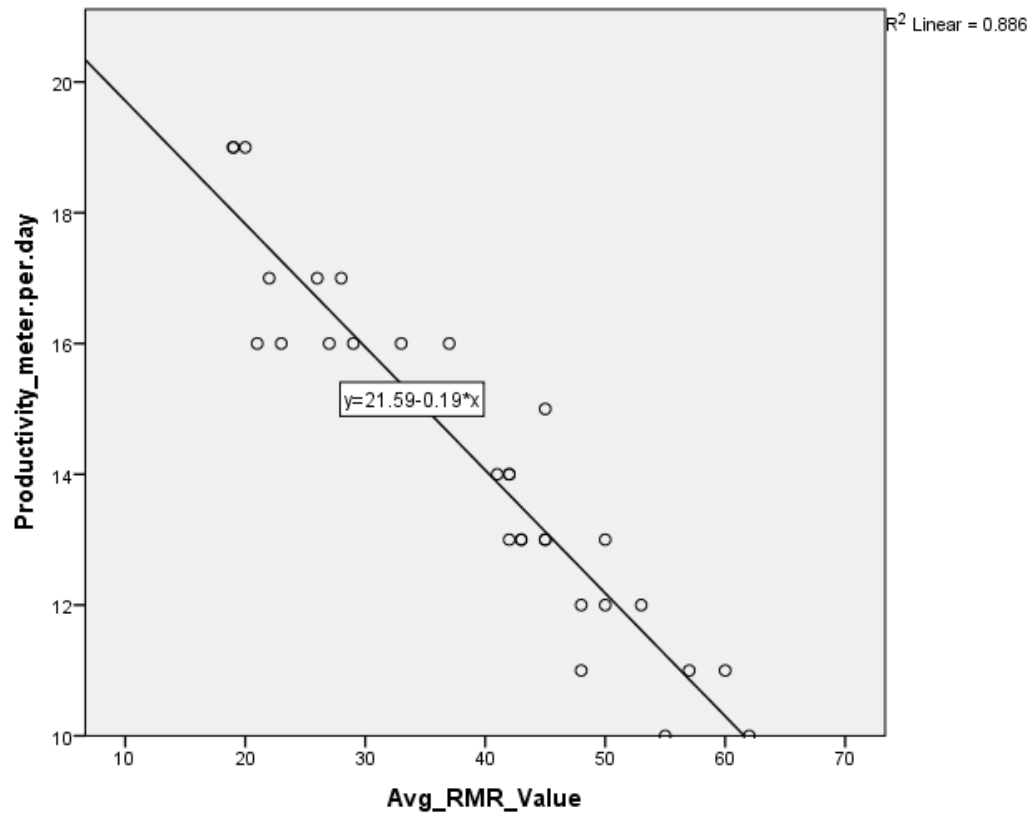
Figure 32 - Average RMR values Vs. Productivity M\day for Tunneling machines > 1500 mm.

As it was expected, the production rates of larger tunneling machines are recorded to be high compared to the smaller ones, since the larger hydraulic pumps capacities used in the control containers and the machines themselves are the main factor causing this variance. Moreover, the higher number of cutting discs used in the large machines is vital for having higher productivities. Furthermore, the machine's own weight as well as its easier access into the excavated tunnel during the excavation process, which can help overcoming several problems that may rise during the excavation process are considered some of the main factors for achieving higher productivities compared to the smaller machines.

However, the constant linear behavior of this correlation reveals the higher production rate stability despite the variance in the RMR values of the rock layers formations against the small sized tunneling machines.

Moreover, figure (32) gives a significant F-value of 2.75E-17 and P-value of 4.4E-23 for the intercept, which indicates the high significance of the relation between the two parameters statistically. This relation gives an upper margin equation of {y = 114.54 - 4.11x}, while the lower margin equation is {y = 97.37 - 5.29x} at confidence level of 95%. This makes the process of estimating the productivities from the RMR values are expressive and reliable for the tunneling machine larger than 1500 mm as well as the smaller tunneling machines as discussed earlier in this chapter.

However, the highest productivity for the large machines was recorded at Al Rayyan Al Gadded and South Qetaifan Island #2 with (RMR: 19 - Productivity: 19 m\day), while the lowest productivity was measured at Abu Nakhla (west Messaid area) with (RMR:62 - Productivity: 10 m\day). These results show that the lowest production rates, for the large diameters recorded at the highest RMR grades, are better than the lowest values of production rates for small diameters machines, revealing that for high RMR grades, it is preferred to excavate using the large diameter machines than using the small diameter ones (if possible) in order to avoid an issue of slow progress that is considered a critical factor for all the involved persons working in a project. Furthermore, the usage of larger diameter tunneling machines (if possible) throughout high RMR grades rock layers is preferred, in order to avoid the buckling problems (banana shape line) that may occur due to the good quality of rock compared to the machine's own weight. This issue is of higher probability when using small diameter machines compared with larger ones.

4.5.4   Financial Evaluation

In order to fully understand the effect of using large diameter tunneling machines during high RMR grades rock layers, a cost per meter value from a financial perspective has been calculated, similarly to the average direct costs that have been calculated for the smaller machines. The average cost fees for this process are as follows:

1. Machine (whole set including separation unit {Herrenknecht A.G. company}, pumps, hoses, cables and diesel) rental fees: 20000 QR/day,

2. Crane rental fees: for machines larger than 1500 mm, a 100 tons crane will be sufficient 60000 QR/month,

3. Labors: for machines larger than 1500 mm, 1 operator +1 Forman + 5 labors are sufficient, 40000 QR/month,

4. Generator: 500 KVA generator is sufficient for these diameters, 15000 QR/month,

5. Materials: including fresh water for excavating and plain concrete for the thrust wall and launching eye, 25000 QR/month, and

6. JCB + Damp truck: for removing the excavated materials which is considered a main factor contributing to the monthly cost for large machines. Since it differs from diameter to another, and it is usually calculated per cubic meter, it was evaluated to have an average of 25000 QR\month.

An average total monthly cost of 765000 QR is estimated for the tunneling process using diameters larger than 1500 mm, presenting a daily cost of 25500 QR which is more when compared to the daily cost of smaller machines (approximately 2.27 times). This raise seems logical due to the larger scale of investments made for these machines and the necessary activity sequences performed during projects of these sizes. An average cost per meter has been calculated by dividing the daily cost with the daily production rates, with the following figure (33) showing this relation.
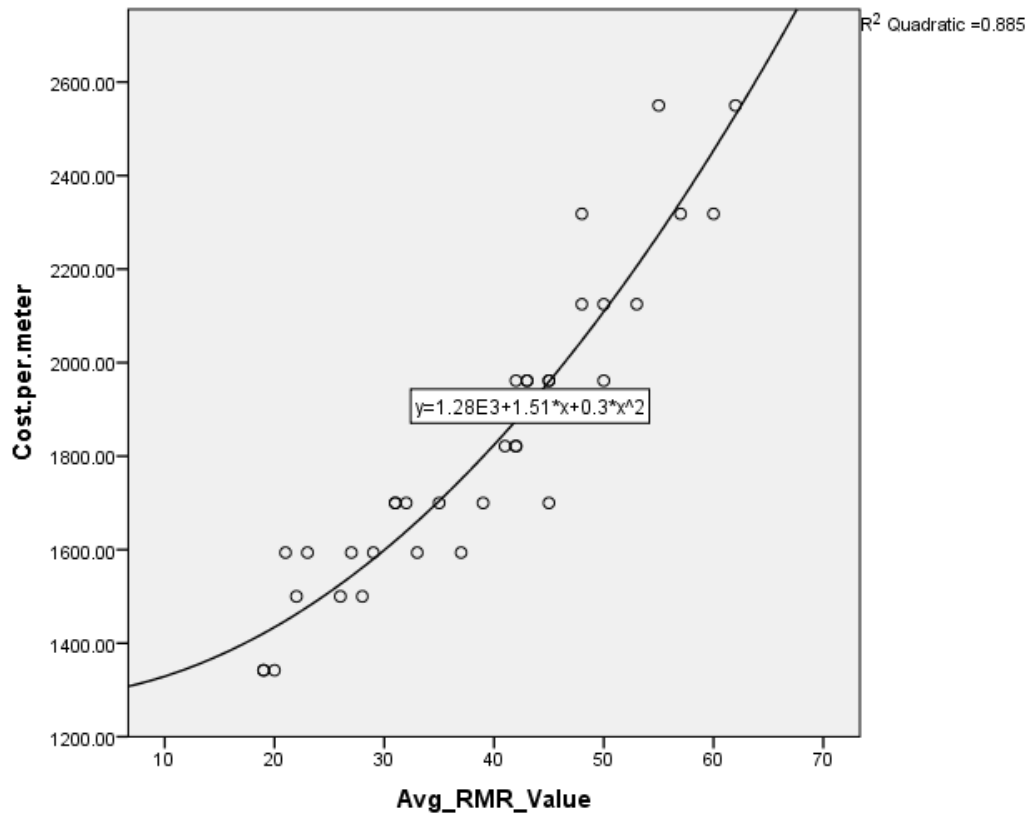
Figure 33 - Average RMR values Vs. Cost per meter (Qatari Riyals) for Tunneling machines >1500mm.

It is apparent that the high daily cost of larger tunneling machines is reflected also to the excavated meter cost, which ranges from 1342 QR - 2550 QR according to the daily production rates.
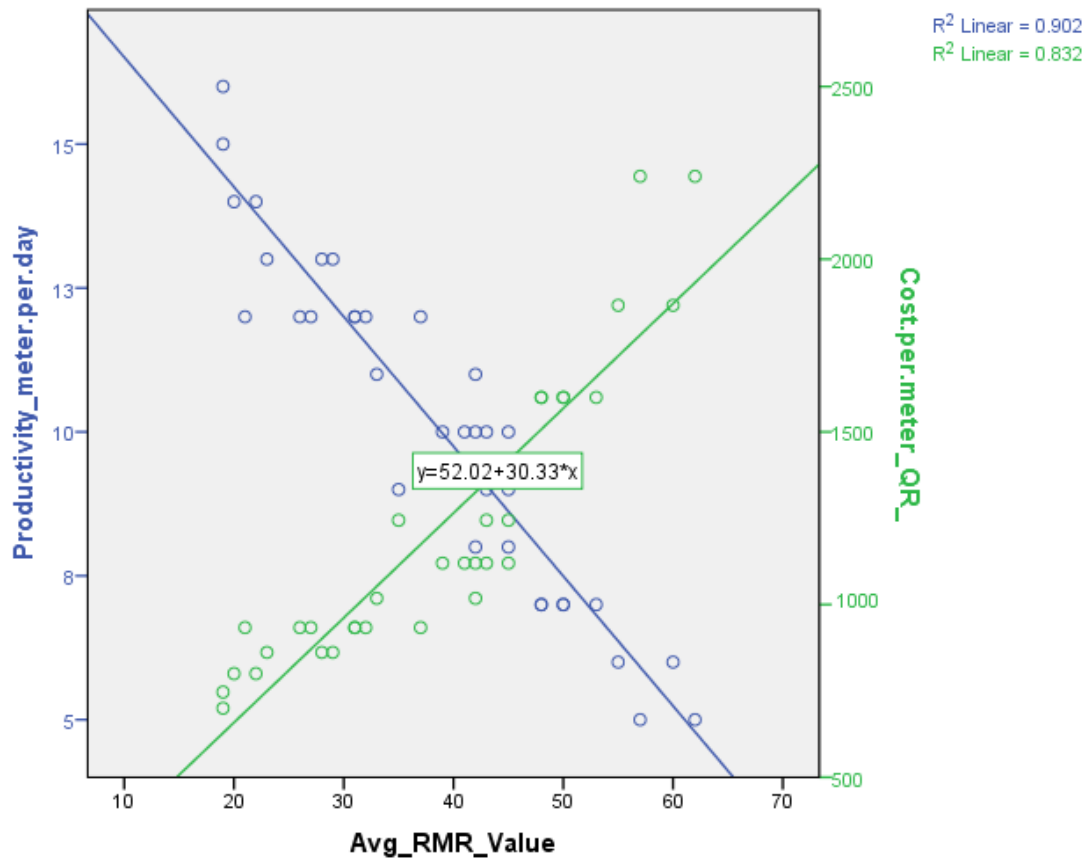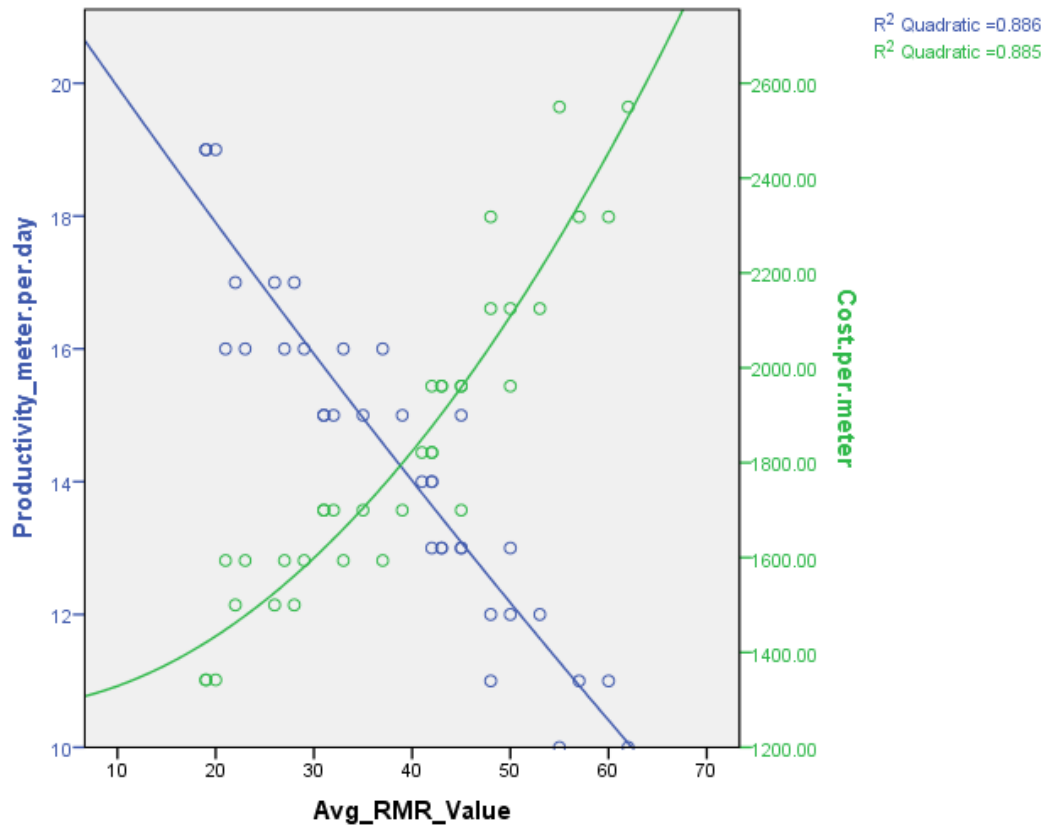
Figure 34 - Average RMR values Vs. Average Productivity M/day Vs. Cost per meter (Qatari Riyals) for Tunneling machines > 1500 mm.

Obviously, the efficiency of using the large machines (if possible) in the high RMR rock layers grades from a financial perspective is better compared to the smaller machines, since, the cost of using the smaller diameters tunneling machines at locations having RMR grade of 62 equals to 2240 QR\m', while using larger diameters machine at the same locations will have an average cost of 2550 QR\m', bearing in mind the higher productivity of using each machine (5m\day for small machines and 10 m\day for large machines which is approximately double values), and the high gained (income) cost per meter of the large diameters tunnels compared to the smaller tunnels (approximately 2-4 times) which reveals the crucial results obtained from using the larger diameters machines for the high RMR rock layers values, the following table (18) shows the difference in the average income net profit for the two classes of tunneling machines, after assuming the average incoming meter cost of each class of machines to be 4000 QR\M for small machines, while it is assumed to be 6000 QR for the large machines. As shown in this table, the

net profit of the large machines is greater than the small machines, which reveals the higher efficiency of using the large machines in rocks with high RMR grades.

Machine Size	Avg. direct Cost/Meter at the highest RMR value (QR)	Productivity M/day at the highest RMR value (QR)	Total Cost\Day (QR)	Meter Price (Income)(QR)	Net Profit\Day (QR)
Tunneling machines < 1500 mm	2240	5	11200	4000	(4000*5) - 11200 = 8800
Tunneling machines >1500 mm	2550	10	25500	6000	(6000*10) - 25500 = 34000

Table 18 - Comparison between the usages of different tunnel machines regarding the net profit in case of excavating in the highest RMR grades rock layers recorded in Qatar

All the previously listed graphs and correlations aim to assist the infrastructure and geotechnical engineers who are involved in the designing, bidding, consulting and executing tunneling activities by providing them the ability to choose the most adequate and reasonable tunneling machine diameter and predicting the average rates of daily production as well as the average cost per meter.

4.5.5   Cutter Head Discs Replacement Intervals

4.5.5.1 RMR Grades and Cutting Discs Replacement Intervals Relationship

An additional parameter, such as the replacement intervals of the cutting discs of the tunneling machine cutter head, has been evaluated through this research. Different values of RMR were studied for determining the influence of RMR to this parameter. The reasons of studying this parameter have been described in details in the previous research approach chapter. It is important to mention that the cutting discs functions are as follows:

1. Crush the excavated material to avoid any big rock masses stuck in the machine head chamber,

2. Enlarge the excavated tunnel around the machine by creating an overcut zone around the tunnel body for decreasing the friction forces that will consequently decrease the required jacking force and will protect the jacked pipes from any damages caused by the high jacking force, and

3. Allow the cutter head to rotate in full capacity which will subsequently improve the productivity of the tunneling machines.

Every tunneling machine comes along with a specific number of discs, designed by the German manufacturer company (Herrenknecht A.G.), to ease the process of excavating, by utilizing certain number of discs for the crushing operation, and several other discs for creating the overcut zone around the tunnel body. A photo for the commonly used discs in Qatar is shown in the following figure (35) which include the single and double edge cutting discs.

Figure 35 - Cutter head for 600 mm tunneling machine using double edges discs.

However, recorded data for the intervals of replacement cutting discs was collected through the studied locations across Qatar for the double edged cutter head discs, with a specific average excavation area for one disc, and a certain tunneling machine thrust force; since every tunneling machine has an excavated area which equals to the area of the outer diameter of the machine including the overcut diameter, divided this area by the number of discs in the machine, an average excavation area of each disc that represents the service area of each disc will be obtained. In order to have a reliable and real comparison between the discs replacement intervals for the different rock layers existed in Qatar, a certain average excavation area of 900 - 1000 cm^2 was studied during this research, also, thrust force for machines diameter ranged between 1000 - 1200 mm were studied, and other values of excavation areas and machine thrust force were excluded, and a relationships between the discs replacement intervals and the RMR values for the excavated rock layers were exported to form the following graphs figure (36).
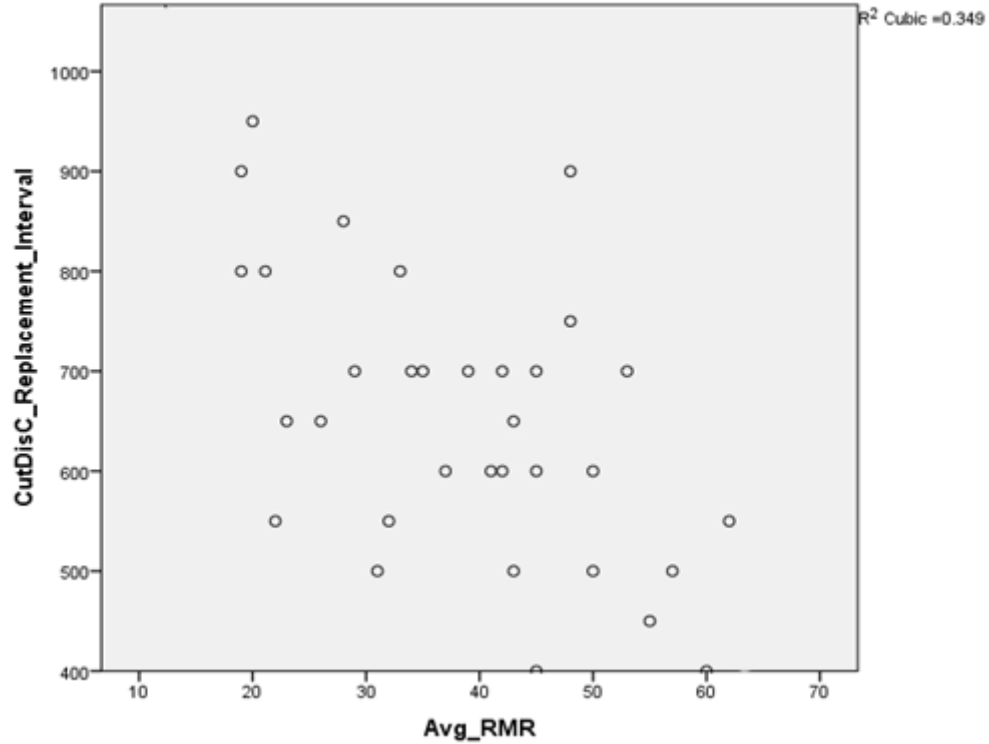
Figure 36 - Cutting Discs Replacement Intervals (M) Vs. RMR grades for different locations across Qatar.

Obviously, disc replacement intervals have a non-stable correlation with the RMR grades, for different sizes of tunneling machines, with the curve being relatively inverse proportional and approximated by a power function. The reason of such behavior is that the RMR rating factors do not affect the disc replacement intervals directly but rather indirectly.

4.5.5.2 Factors affect the Replacement Intervals

Based on previous studies and experts, the cutting disc replacement intervals were observed to depend on combinations of the following factors and are ranked by their priorities:

1. Abrasion grade of the rock layers excavated by the tunneling machines. The higher the abrasion the higher the need of disc replacement within short intervals,

2. Rock strength represented in this research by the UCS values, and

3. RQD%, cohesion and weathering state for the rock layers.

4.5.5.3 Rock Abrasion Cerchar Test

Based on the mentioned factors, Abrasion Cerchar test results ASTM No. D7625-10 (2010) were obtained in the studied locations in order to define the mineral percentage in the rock layers that constitute the rock hardness. Additionally, the relationship of the Cerchar Abresitvity Index (CAI) and the disc replacement intervals is plotted for better understanding of this data dependency, as shown in figure (37).
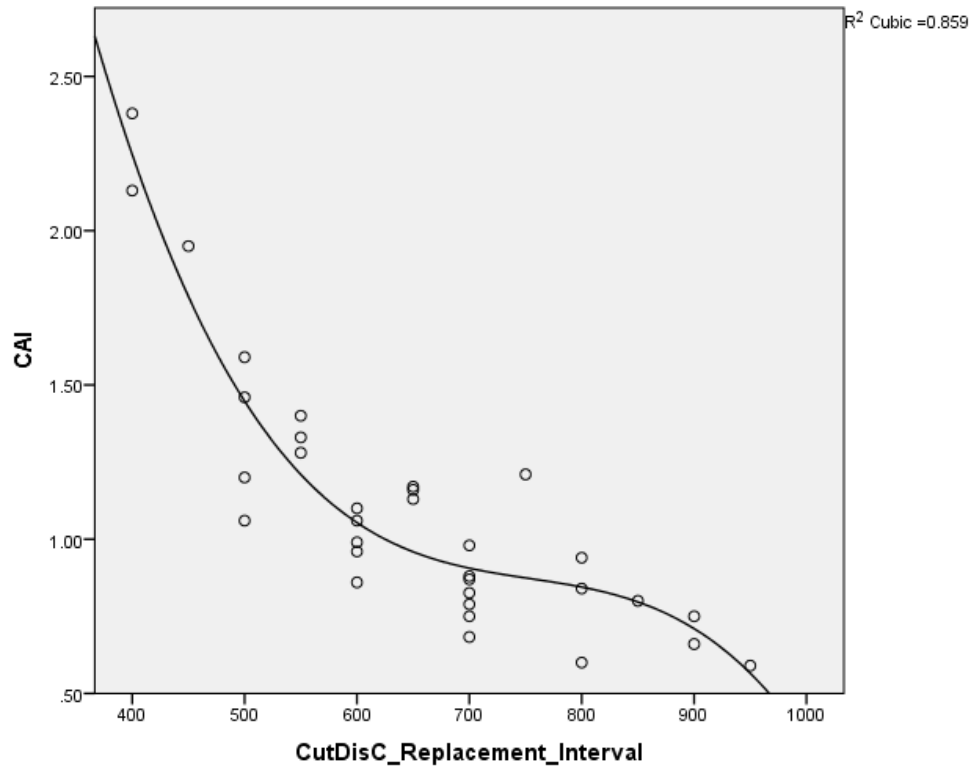
Figure 37 - CAI (Cerchar Abrasivity Index) Vs. Discs Replacement Intervals (M).

An inverse stable relation between the values of the two axes is apparent, revealing the high dependency between the cutting disc replacement intervals and the abrasion of the excavated rock layers, unlike the RMR grades.

Similar to the productivity Vs. RMR values graphs explained earlier in this chapter, it was observed that the presence of any side by side rock layer with another rock layer affects the disc replacement interval, since the lack of mineral materials that caused to increase the abristivity behavior of the rock layer, and the plasticity features of the cohesive materials in the Midra Shale layers for example may somehow increase the average replacement intervals. On the other hand,

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the presence of Simisma limestone layers and Rus formation layers increase the abrasion properties of the layers, due to the existence of Calcium Carbonate materials in their contents, that results to decrease the expected intervals of the discs replacement.

It is highly recommended to calculate a weighted average compressive strength value in order to get the real value of compressive strength acting on the Cutter head discs, in order to have a full estimation for the wearing behavior of the used discs. The following equation is proposed for calculating the weighted compressive strength:

$$UCS_w = 1/2 \{(UCS_1*t_1 + UCS_2*t_2)/t_1+t_2 \quad + \quad (UCS_1*w_1 + UCS_2*w_2)/w_1+w_2) \qquad \text{Equation (6)}$$

Where,

UCS_w: average weighted UCS value,

UCS_1: UCS value of the first layer,

t_1: Percentage of first layer thickness in the excavated layer thickness,

UCS_2: UCS value of the second layer,

t_2: Percentage of second layer thickness in the excavated layer thickness,

w_1: Percentage of first layer abrasitivity index to the second layer abrasitivity index,

w_2: Percentage of second layer abrasitivity index to the first layer abrasitivity index.

The above equation uses the thickness and abrasitivity index for both layers contributing in the excavated rock layer for calculating the expected UCS value based on their thickness and abrasion.

However, it is important to state the other factors that affect the cutting discs replacement interval that must be controlled and included with the studied factors, these factors are as follow:

1. Tunnel length; the longer tunnels will be exposed to less discs replacement interval, since the excavation continuity for long durations causes high wearing for the discs due to the high temperatures result from the rock excavation that may face the cutter head discs, which compose the main reason of wearing in these cases.

2. Machine Operator Skills; operating tunneling machines in rocks layers impose the operator to be more accurate and aware with the different machine parameters, since the high recorded cutting head pressures may lead to quick wearing of the cutting discs.

3. Machine Maintenance; since the periodic maintenance of the tunnelling machine specially the cutter head teeth that need to be welded from time to time leads to have high discs replacement intervals.

Figure 38 - AVN 600mm tunneling machine with double edges cutting discs.

4.6 Data Analysis: Excavation

4.6.1 Excavation Methods

Generally, three excavation methods are usually performed namely the Digging, Ripping and Blasting (Tsiambaos and Saroglou, 2010). A detailed review for each method is presented by MacGregor et al., (1994) and Basarir and Karpuz (2004). The ripping method is usually preferred compared to free digging since it is less time consuming and more cost effective than blasting despite the progressive ripping performance decrease when the ripper tips are starting to wear out. Evaluations concerning material ripping characteristics have been developed based on several aspects; compressive strength (Weaver, 1975, Kirsten, 1982, Smith, 1986, Singh et al., 1987, Karpuz, 1990, Kramadibrata, 1998), weathering degree and spacing of discontinuities (Pettifer and Fookes, 1994) as well as seismic velocity (Catterpillar, 2008). In Qatar, ripping methods using the jack hammers breakers are widely used, although the ripping method is selected only when the compressive strength of the material is between 10 and 25 MPa, while blasting is used in cases of a compressive strength above 25 MPa (Bieniawski, 1989). Most of the contractors tend to use jack hammer rippers for the majority of the rocks that usually exceed 25 MPa in compressive strength for several reasons such as;

1. Ripping allows the ground surface rock to be broken into small, easy to handle and transport rubble which can be later removed,

2. The wide availability of jack hammer excavators across the country, and

3. Potential risks of the rock blasting methods which need numerous permissions from different governmental authorities, which makes it a time consuming process.

4.6.2 Productivity and RMR Values Relationship

Concurrently, a geotechnical survey was conducted at numerous locations having excavation projects across Qatar, and as previously discussed, a questionnaire was filled by experts answering several questions related to the following data;

1. Productivity for the excavation works,

2. Methods of excavation,

3. Average depth of excavation, and

4. Equipment used in the excavation process.

Geotechnical soil investigation reports were studied at each surveyed location, however, a large number of excavation projects have been already studied in the previous tunneling projects, since it is common that these two activities are overlapped at a single project.

MacGregor et al.,(1994) proposed that the material's ripping characteristics can be categorized by an initial ripping productivity in $m^3\backslash h$; this criterion can be used when considering ripping as a preferable solution at any situation.

Due to the large number of jack hammer breakers used in Qatar, it was decided to select a single specific equipment for the case study. The equipment selection was done after performing a deep analysis on the obtained survey results, which show that the Komatsu PC400-6 and all equivalent breakers with same capacity and horse power are considered the most widely used equipment in the Qatari market. The features of this breaker are given in the following table (19). This selection will help this research to provide more reliable productivity estimations for the different rock layers in Qatar, and illustrate the impact of RMR differences on the recorder production rates in the state.

Excavator Name	Power	Power Measured	Number of Cylinders	Operating Weight
Komatsu PC400-6	305.8 hp	2050 rpm	6	41400 kg
Caterpillar 336E H	308 hp	2050 rpm	6	37200 kg

Table 19 - Properties of the hydraulic excavators breakers used in this research.

Based on this, a correlation between the average recorded productivities and the RMR grades has been exported, with two separate graphs depicting this correlation. More precisely, the first graph of figure (40) shows the correlation for average given excavated depths of up to 8 meters, while the second graph of figure (41) illustrates the association for average depths of more than 8 meters. As it can be seen, the excavated depth is a crucial factor that affects the productivity, since the sequences of excavation might change during an increase of the excavation depth. For example, during a visit to project located at Maiuther south west area, it was observed that due to

the relatively deep excavation depth of seventeen meters, the contractor decided to drop the jack hammer excavators down in the excavated shaft along with other work progress, as shown in figure (39).

Figure 39 - Excavation at depths > 8m using rippers at the level of excavation.

As shown in this figure, this decision required a crane for dropping the equipment, JCB bucket for the excavated materials removal and labors to guide the excavator operator as well, which largely affect the whole process productivity decreasingly.
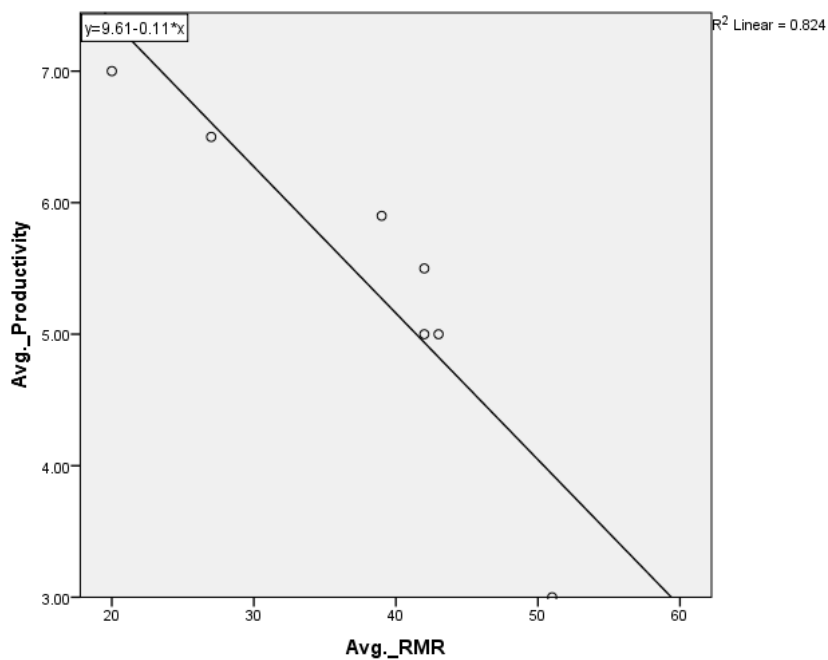
Figure 40 - Excavation Productivity (M^3\hr) Vs. RMR grades for depths < 8m.
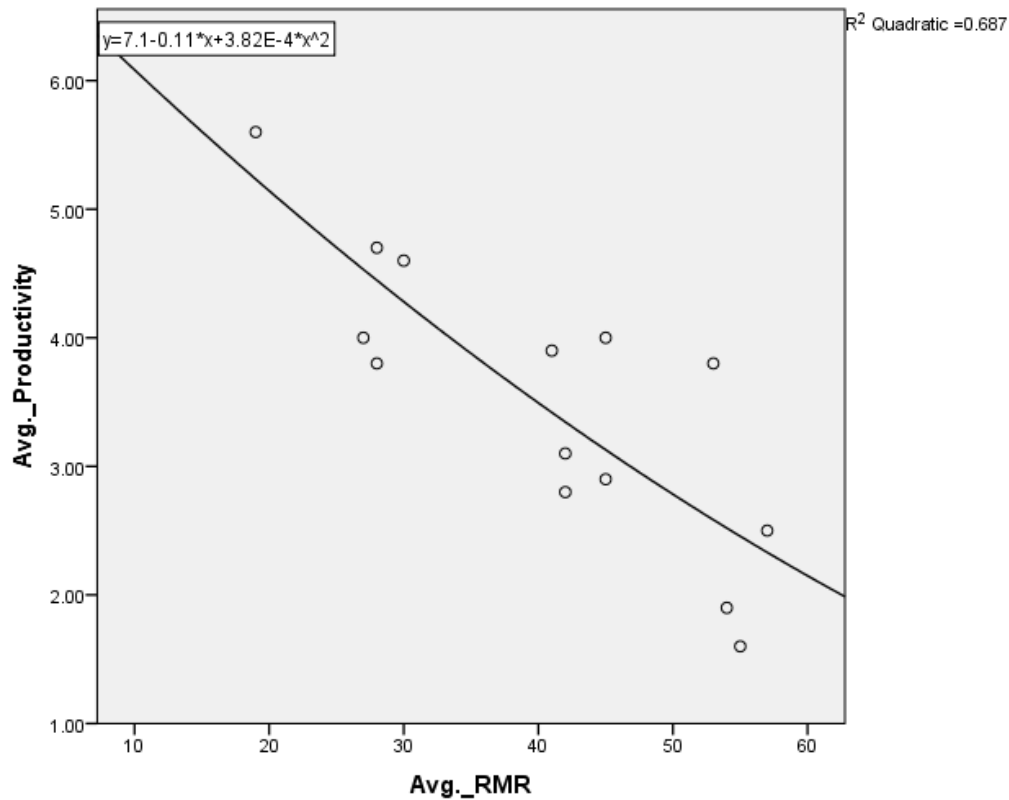
Figure 41 - Excavation Productivity (M^3\hr) Vs. RMR grades for depths > 8m.

Observations on figures (40),(41) indicate that the correlation between the productivity rates and the RMR grades tend to be linear, with a confidence interval equals to +\- 17 (for the depths less than 8 meters) and +\- 15 (for the depths greater than 8 meters), and a confidence level of 95% for both relations, these statistical results present the RMR classification system as a reliable tool for predicting the excavation productivities in Qatar, since the principal factor for the RMR ratings are similar to the evaluated rocks' ripping characteristics, mentioned earlier in this section and are listed as follows;

- Compressive strength,

- Weathering degree,

- Joints spacing, and

- Seismic velocity.

Apart from the last factor, all the other aspects that affect the ripping features are deeply considered in the RMR rating. In order to study the relations between the recorded productivities and the rock parameters, figures (42), (43), (44) and (45) represent the recorded productivities against the obtained RQD%, and these productivities verses the compressive strength results obtained from UCS tests, for both excavation depth classes (less and greater than 8 meters) respectively.
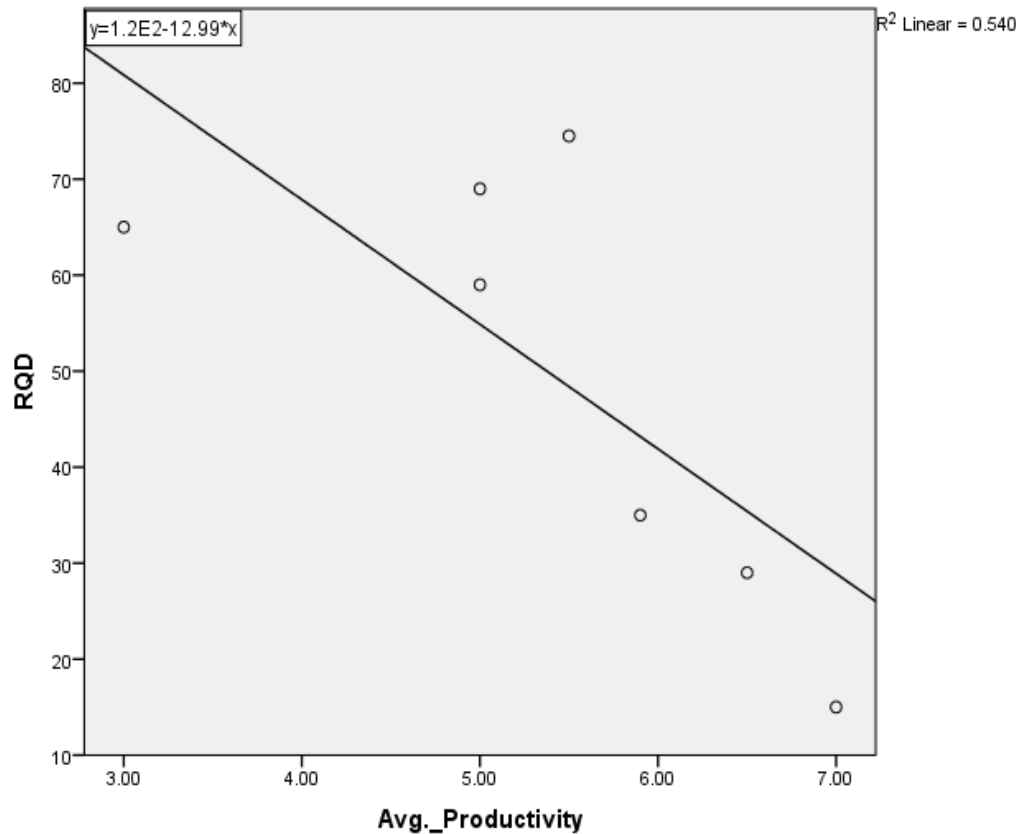
Figure 42 - RQD% Vs. Average excavation productivity (M^3\hr) for excavation depth <8 m.

Figure 43 - UCS values Vs. Average excavation productivity (M^3\hr) for excavation depth < 8m.

At figures (42) and (43), it is observed that the highest productivity was recorded at (Salwa Road - Ramada signal area) which has the lowest RQD% but not the lowest UCS value, while the lowest productivity was found at (Al Nasr Road- Al Sadd area) that gives the highest UCS values but not the highest RQD%. These two locations were studied, and it was revealed that the highest productivity was recorded at locations that contains weathered Simsima limestone, that has the lowest RMR grade among all the studied location with very wide joint spacing, open fractures and wet samples, that drive this location to be the highest excavation production rate among all the other locations, this results prove that RMR grade is the most reliable parameter to describe the rock rippability, since it concerns about several properties of the rock sample that are considered the main factors affecting the excavation productivity.
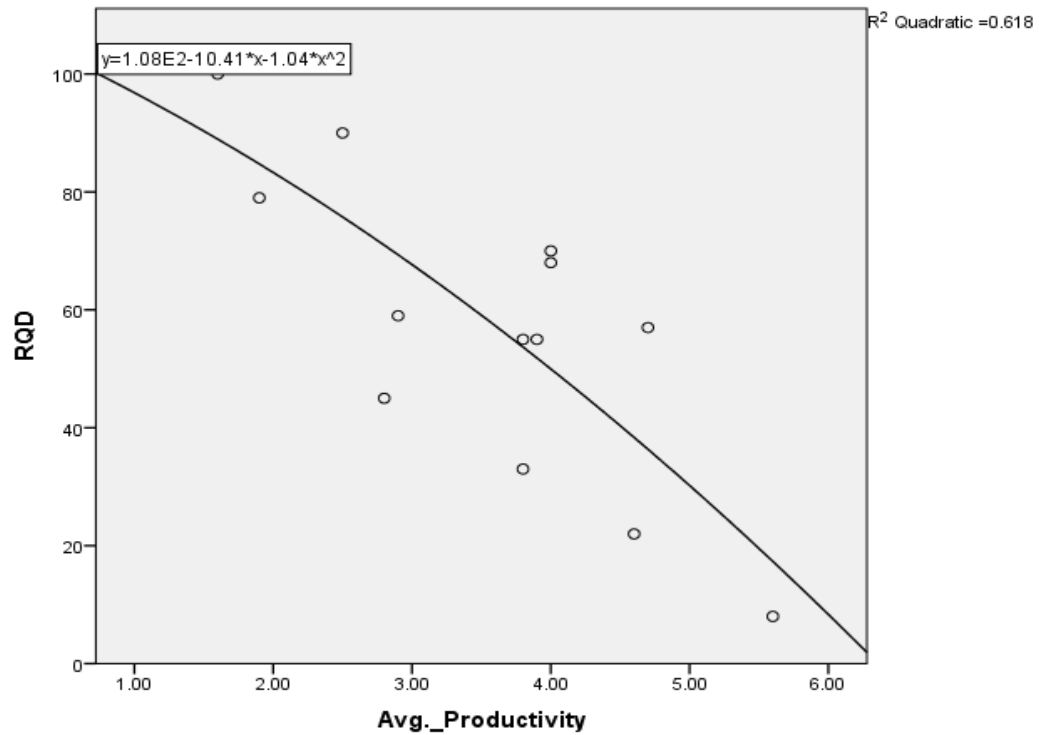
Figure 44 - RQD% vs Average excavation productivity (M³\hr) for excavation depth > 8m.

Figure 45 - UCS values (MPa) vs Average excavation productivity (M³/hr) for excavation depth > 8m.

Similarly, figures (44) and (45) show the same correlations for the excavation process recorded at depth greater than 8 meters, the lowest productivity was found at (Mauither South West Doha area) that RQD% was obtained to be the highest grade among all the other locations (100%), while the UCS value was relatively high but not the highest obtained value. Meanwhile, The highest productivity was recorded at (Al Rayyan Al Gadded area) with RQD% observed to be the lowest, and low UCS value but also not the lowest value among the other locations obtained values. Studying these results and analyzing the other rock properties at these two locations and the other locations have revealed that all the previously mentioned factors combined form the rock rippability behavior, these factors are the considered the major factors used for the RMR rating system, which reveal the importance of the RMR classification system as an adequate system for the judgment of the rock ability to be ripped. Due to this, figures (40), (41) can be considered as reliable tools for predicting the productivity rates for any rock layer after obtaining its RMR grade.

It is worth to be mentioned that in an area located north of Doha city namely Smesma, a blasting excavation method was selected due to the highly notable quality of the existed rock layers. Unfortunately, the average rock parameters of this site and the excavation productivity rates were unavailable for the author.

Chapter Five: Conclusion and Future Recommendations

5.1   Conclusion

This research presented a complete geotechnical study concerning the rocks in the state of Qatar. More precisely, it studied the impact of different rock properties and behaviors on two main civil applications namely the Tunneling and the Excavation. During this study, several rock samples were collected and numerous soil investigation reports from different locations across Qatar were studied in order to acquire the required parameters that were necessary for the proposed rock classification system. Furthermore, a classification system namely the RMR (Rock Mass Rating) system was utilized to classify the rock samples in this research, and study the relationships between the obtained RMR values and two main rock parameters (RQD%, compressive strength). In addition, two questionnaires were prepared and filled by experts during the site visits (thirty six tunneling projects, and twenty two excavation projects) in order to collect rich and real survey recordings for establishing reliable and expressive correlations between the different average RMR grades and the corresponding recorded values of production rates for both tunneling and excavation applications.

Results from the tunneling process were separated into two classes due to the technical reasons mentioned earlier in the data analysis chapter; results for tunneling machines less than 1500 mm diameters, and results for machines more than 1500 mm. Moreover, cutter head disc replacement intervals were collected during the sites visits in order to study the impact of the different RMR grades on the replacement intervals.

Furthermore, the excavation process was classified according to excavation depths due to the notable influence of the excavation depth on the recorded productivities. As a result, the recorded productivities were separated into two classes; excavation depths of 8 meters or less, and excavation depths greater than 8 meters. The collected productivities are based on excavator jackhammer rippers that have similar hydraulic and mechanical properties to the most commonly used excavator in Qatar, the Komatsu PC400-6.

Generally, this research's motivation was to identify existed rocks engineering properties in Qatar, and their impact on two main construction and infrastructure applications from a geotechnical engineering perspective.

Based on the scope of this work, the collected data and the analysis, the following can be concluded:

-Qatargeology formations survey.

- Simsima limestone layers are considered the major component of the subsurface layers and are widely spread across the country in an average depth of 30 meters, which is considered for most critical depth for the civil applications that take place in Qatar. Midra Shale and Rus formation layers existed at several locations as well.

- Based on several experts past experience, a general Qatari rock map was also developed, providing the five most prominent zones according to rocks general quality existed in Qatar.

- RMR grades were also obtained for different collected samples from numerous locations across Qatar. The obtained results indicated an average value of 41 (poor to fair rock) for the tested samples.

- Three rock layers found in the tested samples (Simsima limestone, Midra Shale and Rus formations).

- Three tools were justified for calculating the RMR number for the tested samples as follows:

1. Tables proposed by Bieniawski's (1976, 1989),
2. An online free tool that can be found online at www.mining.com, and
3. Graphs presented by Erik Eberhardt- UBC Geological Engineering.

- The utilized Bieniawski's tables provided the same results with the online tool, while Erik Eberhardt-graphs offered higher values due to the different rating method used for the weathering state and joint condition.

- Simsima limestone is found to have the highest average value of RMR (42), while Midra Shale layers recorded an average value of (38) and Rus formations a value of (29).

- Two main rock parameters were studied from the tested samples which are the RQD% (Rock Designation Quality), and the compressive strength, obtained from the unconfined compressive UCS strength tests. It was found that Smisma limestone layers recorded the highest average

UCS, due to their formation components, while Midra Shale layers gave the highest RQD% values, due to the deep layer existence levels and the particle cohesion forces caused by the component cohesive materials. Rus formations presented the lowest values of RQD% and UCS, since they contain soft and highly weathered limestone in their formations.

- RMR grades show a high dependency with the RQD% values. A reliable linear relationship between these two parameters is established, due to the high RQD% contribution on the rating system, which enabled the author to propose an expressive tool for determining accurately the RMR grade for any rock sample in Qatar by providing only the RQD% value of the sample.

- Similarly, a non-linear relationship between the UCS values and the calculated RMR grades was determined and observed, due to the normal contribution of the compressive strength on the RMR rating system.

- Based on the average RMR grades of the existed rock layers in the studied locations, a map for Qatar was developed for depths ranging from 10-20m, in order to illustrate in one single map several parts of the current research results.

- Production rates for thirty six tunneling projects were recorded for analyzing a potential relationship between productivity and the corresponding RMR grade of the excavated rock layers. A linear and stable relationship was observed between these two parameters, which reveals the strong impact of the RMR grade on the tunneling productivity for both large and small tunneling machines, also, it states how expressive the RMR classification system for the tunneling process is. Moreover, large diameters machines recorded higher productivities than the smaller ones, due to several mechanical and technical reasons, mentioned in details in the data analysis chapter. Furthermore, a function curve was established based on the studied data, in order to provide a reliable tool which is able to predict the expected productivity for the tunneling machines provided the RMR grade of any rock sample bored in Qatar.

- For the tunneling process, an average direct cost per meter was calculated, in order to fully understand the RMR grade impact on the average productivity with a simultaneous effect on cost per meter as well. As a result, the average tunneling direct cost per meter in machines less than 1500mm diameters range from 700 QR, for the lowest RMR grade, to 2240 QR for the highest RMR value, while ranging from 1342 QR to 2550 QR for all the RMR grades. These results

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revealed the importance of the necessary RMR grading before the initiation of tunneling projects, since it could assist the project decision makers to predict a priori the average cost per meter for the planned tunneling activities.

- Financial analysis revealed the high efficiency of the large diameter machine usage at high RMR grades rocks, compared to the small diameter ones. Their higher productivity resulted to greater average net profit, despite their higher operational costs.

- Data for Cutter head Disc replacement intervals for a service area of 900-1000 cm2 per each disc (manufactured by Herrenknecht A.G.), was collected and found to have an indirect dependency with the RMR rock grades. More precisely, a non-linear and instable inverse proportional correlation was recorded, while a stable and obvious inverse proportional relationship was determined between these intervals and the Cerchar Abrasitivity Index CAI, reflecting the high dependency of the replacement intervals on the excavated rocks abrasion behavior.

- Ripping excavation method constitutes the main used method all over Qatar, although rock blasting method is considered the most adequate excavation method for the type of rocks in Qatar, with their compressive strength exceeding 25 MPa in typical cases. However, the ability to implement this method is quite difficult due to the potential risks that might appear during rock blasting. Furthermore, the authorization approvals for this type of work is considered a time consuming process.

- The average collected excavation productivities, for both depth classes, exhibited a stable and clear inverse relationship with the RMR rock grading in all the different studied locations. However, a questionable relation between RMR rock grading and the corresponding RQD% and compressive strength UCS results, revealed the significant importance of the proposed RMR classification system. The proposed system can be considered a necessary and adequate tool for the judgment of the rock ability to be ripped, since it combines the most prominent factors that influence the rock rippability. Due to this, the chart between the RMR grades and the average productivities can be considered as a reliable instrument for obtaining the average production rate for any rock layer existing in Qatar.

5.2 Future Recommendations

Numerous civil applications in the geotechnical field take place in Qatar nowadays, such as; retaining structure installments, piles excavation, and dewatering applications. A similar research taking into account these applications which can provide accurate and helpful tools for predicting several parameters will be helpful. This research can further ease the process of designing, bidding and execution of these civil applications based on recorded data collected at different locations across Qatar.

On the other hand, other rock classification systems can be implemented to further enrich the geotechnical studies in Qatar, since the variance in classification methods will assist the geotechnical engineers in the better understanding of the properties of the existed rocks. In such way, they can predict rocks' behavior and the expected impact of these layers on the various civil application parameters.

It is believed that achieving the research goals, and studying more civil applications from the geotechnical engineering perspective, will help the next generation to have better chances for the usage of the natural resources in order to live a better life.

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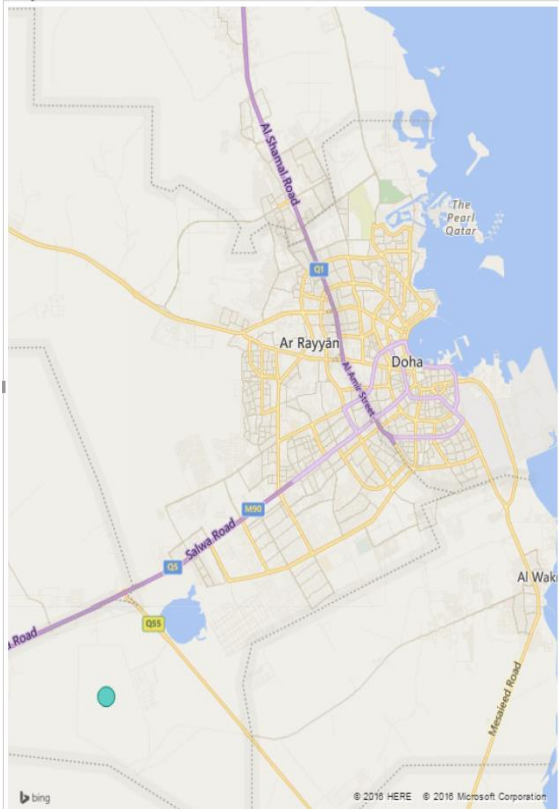
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Appendix -A

Project Name	Rock Layer	Average RMR Value ▼	Rock Grade
Abu Nakhla (west Maissed)	Simsima Limestone	50	Poor to Fair Rock

Project Name

- ■ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-we...
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value ▼	Rock Grade
Al Birka (North East Qatar)	Rus Formation	50	Poor to Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ■ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-we...
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value ▼	Rock Grade
Al Bustan St. Rayan	Simsima Limestone	48	Poor to Fair Rock
Al Bustan St. Rayan	Midra Shale	30	Very Poor to Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ■ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-we...
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value ▼	Rock Grade
Al Innabi St.	Simsima Limestone	39	Poor Rock
Al Innabi St.	Midra Shale	34	Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ■ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-we...
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

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Projects Location		Project Name	Rock Layer	Average RMR Value ▼	Rock Grade
		Al Kheesa East (Rawdet el Hammam)	Rus Formation	26	Very Poor to Poor

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Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ■ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-we…
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location	Project Name	Rock Layer	Average RMR Value ▼	Rock Grade
	Al Kheesa North	Rus Formation	23	Very Poor to Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ■ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-we...
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location			

Project Name	Rock Layer	Averag...▼	Rock Grade
Al Muntazah - Abu Hamour ...	Midra Shale	42	Poor to Fair Rock
Al Muntazah - Abu Hamour ...	Simsima Limestone	37	Poor Rock

Project Name

☐ Abu Nakhla (west Maissed)
☐ Al Birka (North East Qatar)
☐ Al Bustan St. Rayan
☐ Al Innabi St.
☐ Al Kheesa East (Rawdet el Hammam)
☐ Al Kheesa North
�■ Al Muntazah - Abu Hamour (south-we...
☐ Al Rayyan Al Gaded
☐ Al Salam St.
☐ Al Wajba St.
☐ Al Wakrah West Area
☐ Gharafet Al Rayyan
☐ Industrial Area St.53
☐ Khalifa St.
☐ Lusail
☐ Maisaed
☐ Mauthier South west Doha
☐ North East Wakrah
☐ North Qetaifan Island
☐ Rayyan Rd.
☐ Road A3- North West Lusail
☐ Souq Najda
☐ South Qetaifan Island #2
☐ South Qetaifan Island #3
☐ South West- North Qetaifan Island
☐ Wakrah Main Corridor
☐ West Al Khor

Projects Location		Project Name	Rock Layer	Averag... ▼	Rock Grade
		Al Rayyan Al Gaded	Simsima Limestone	19	Very Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ■ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
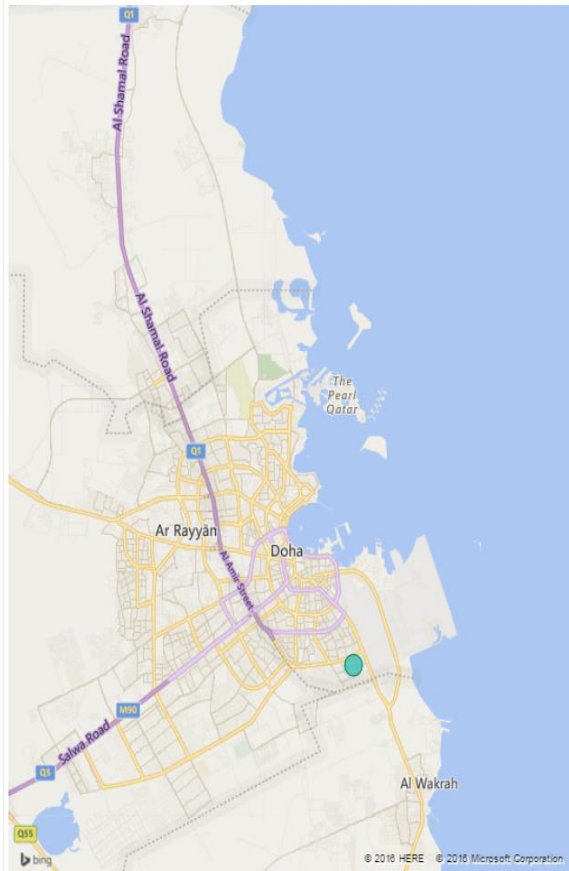- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location		Project Name	Rock Layer	Average RMR Value	Rock Grade
		Al Salam St.	Simsima Limestone	53	Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☑ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
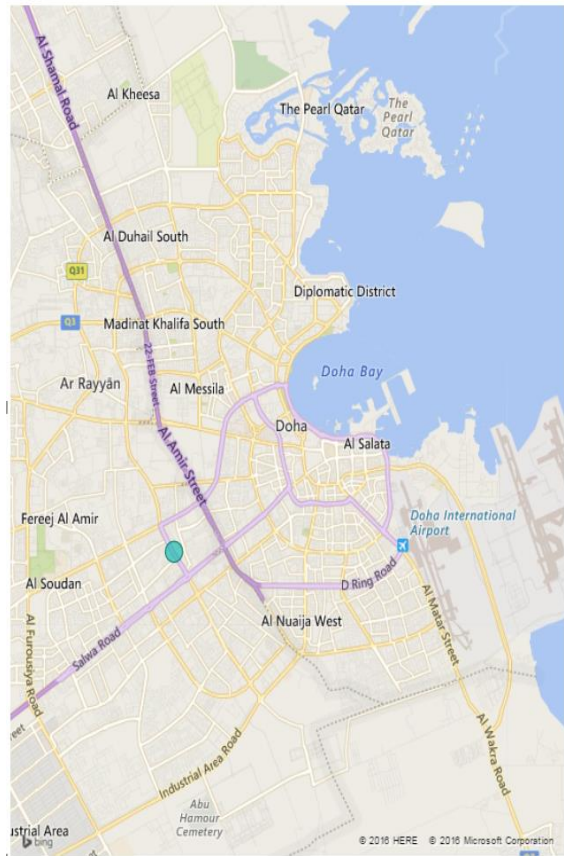- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value	Rock Grade
Al Wajba St.	Simsima Limestone	42	Poor to Fair Rock
Al Wajba St.	Midra Shale	34	Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☑ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
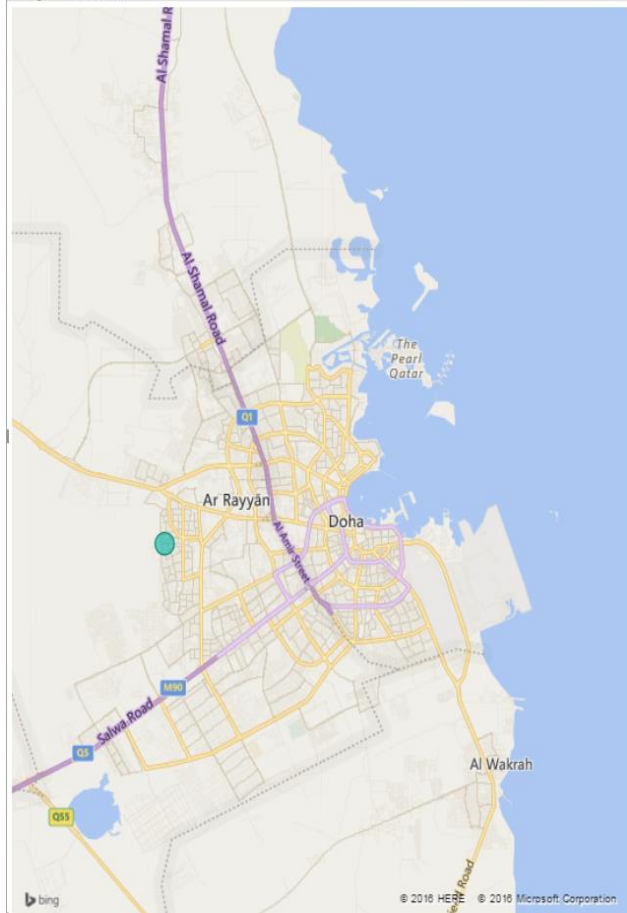- ☐ West Al Khor

Projects Location		Project Name	Rock Layer	Average RMR Value	Rock Grade

Project Name	Rock Layer	Average RMR Value	Rock Grade
Al Wakrah West Area	Simsima Limestone	48	Poor to Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☑ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

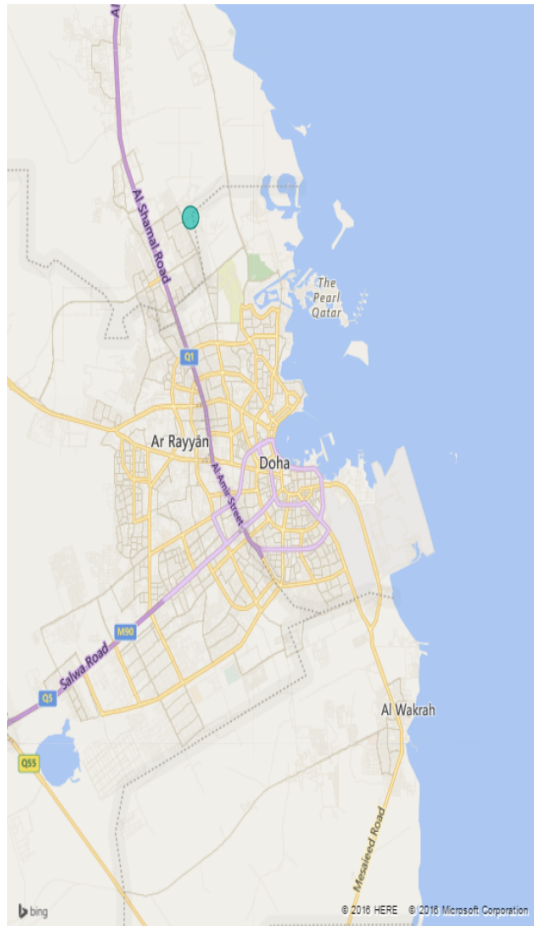| Project Name	Rock Layer	Average RMR Value	Rock Grade
Gharafet Al Rayyan	Midra Shale	45	Poor to Fair Rock
Gharafet Al Rayyan	Simsima Limestone	45	Poor to Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ■ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
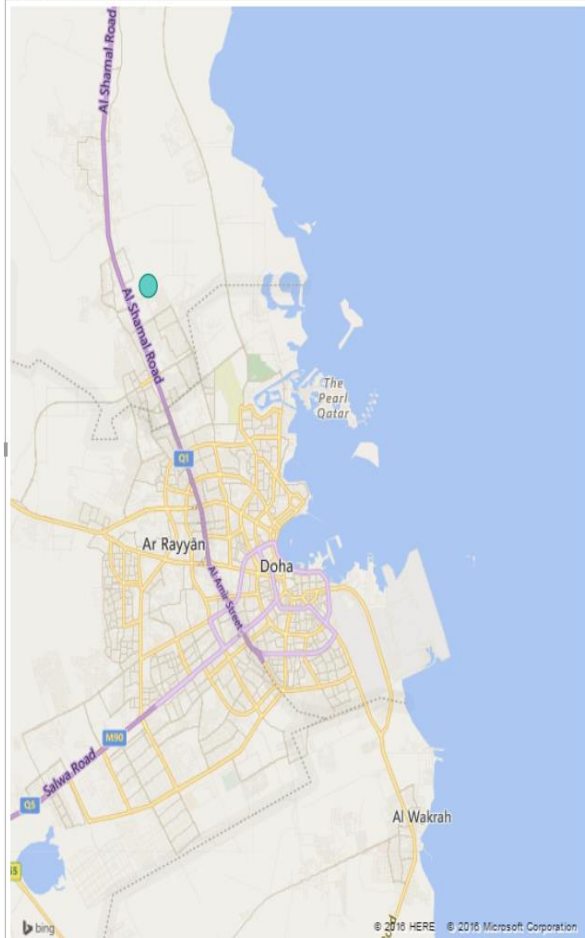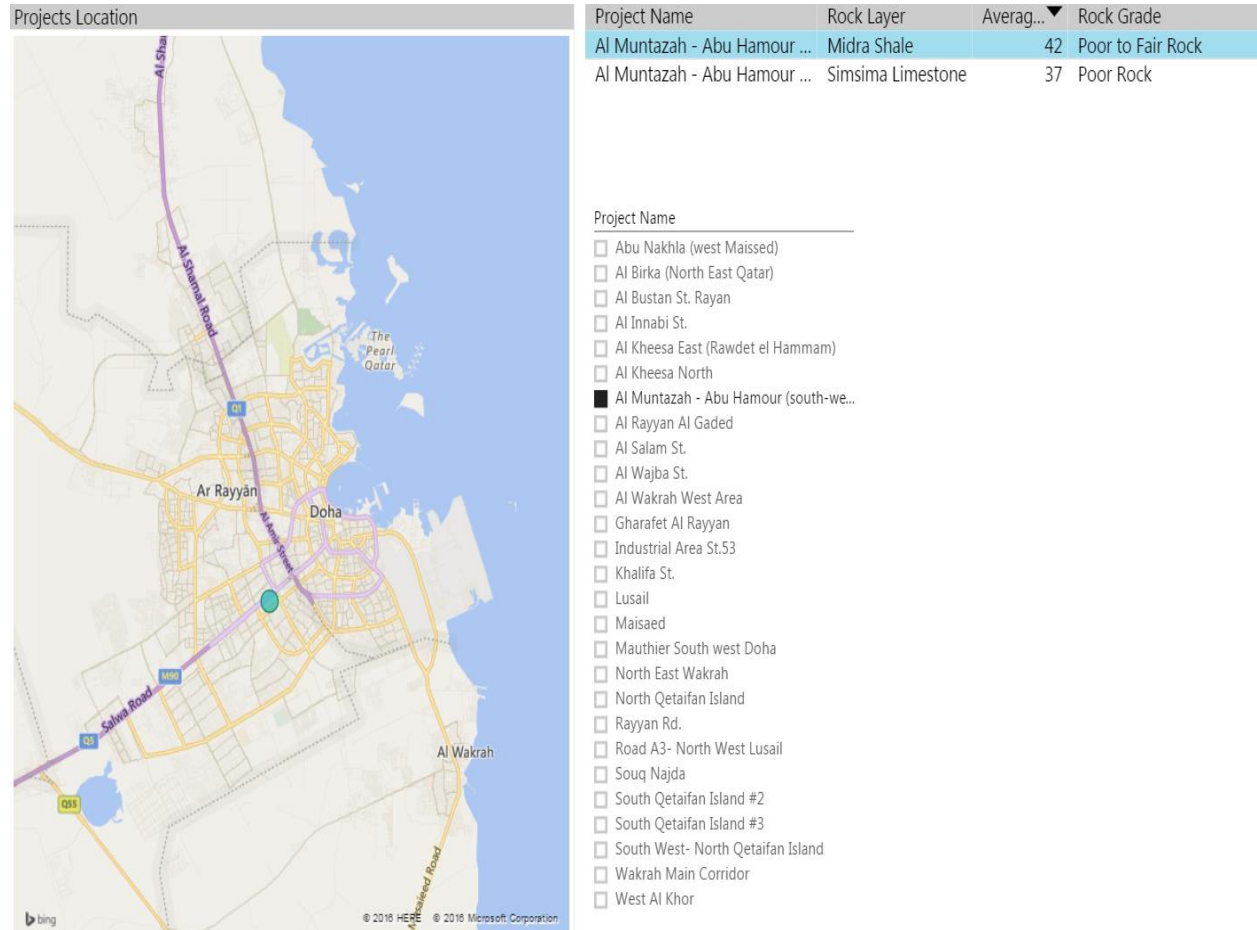- ☐ Wakrah Main Corridor
- ☐ West Al Khor

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Project Name	Rock Layer	Average RMR Value	Rock Grade
Industrial Area St.53	Simsima Limestone	37	Poor Rock

Project Name

☐ Abu Nakhla (west Maissed)
☐ Al Birka (North East Qatar)
☐ Al Bustan St. Rayan
☐ Al Innabi St.
☐ Al Kheesa East (Rawdet el Hammam)
☐ Al Kheesa North
☐ Al Muntazah - Abu Hamour (south-west Doha)
☐ Al Rayyan Al Gaded
☐ Al Salam St.
☐ Al Wajba St.
☐ Al Wakrah West Area
☐ Gharafet Al Rayyan
■ Industrial Area St.53
☐ Khalifa St.
☐ Lusail
☐ Maisaed
☐ Mauthier South west Doha
☐ North East Wakrah
☐ North Qetaifan Island
☐ Rayyan Rd.
☐ Road A3- North West Lusail
☐ Souq Najda
☐ South Qetaifan Island #2
☐ South Qetaifan Island #3
☐ South West- North Qetaifan Island
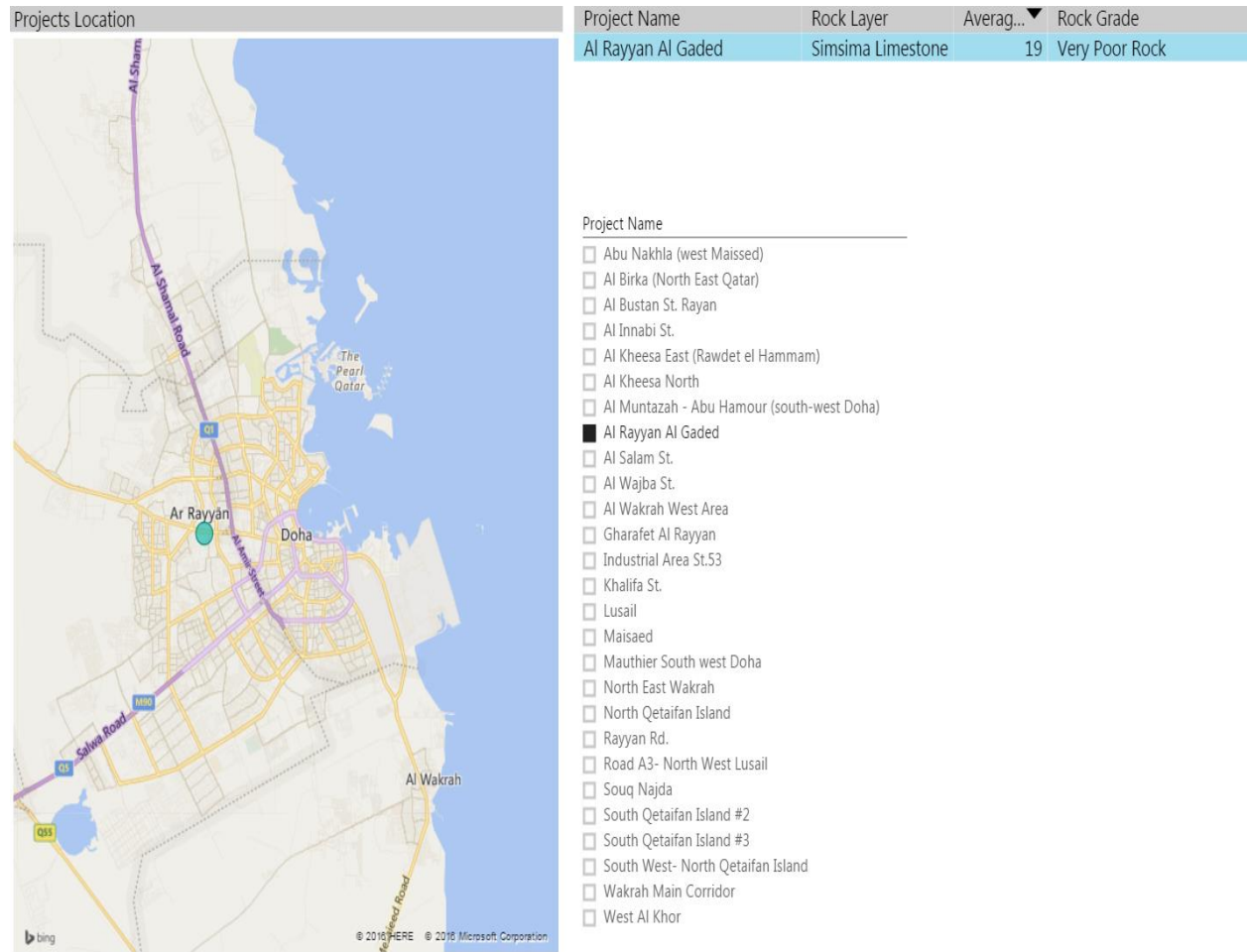☐ Wakrah Main Corridor
☐ West Al Khor

Projects Location

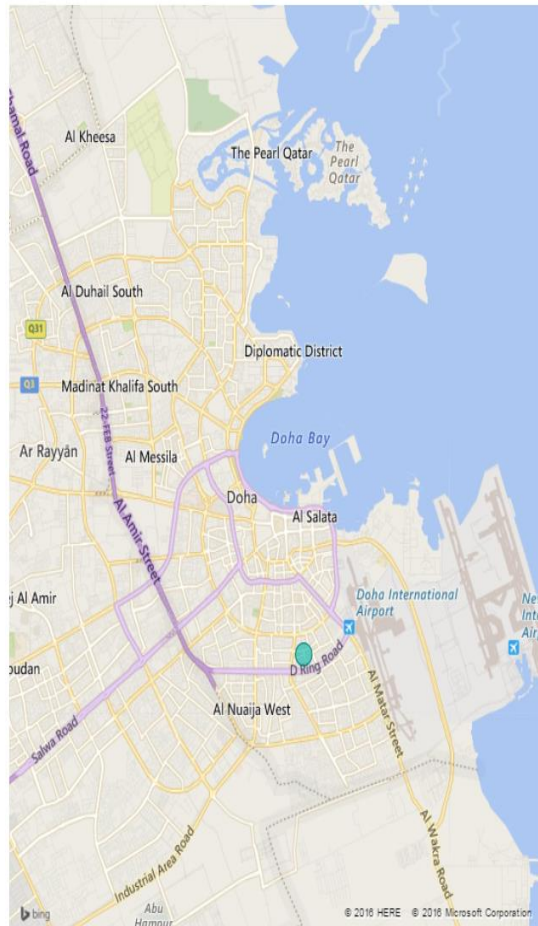| Project Name	Rock Layer	Average RMR Value	Rock Grade
Khalifa St.	Rus Formation	30	Very Poor to Poor Rock
Khalifa St.	Simsima Limestone	39	Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ■ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location		Project Name	Rock Layer	Average RMR Value	Rock Grade
		Lusail	Simsima Limestone	34	Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ■ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
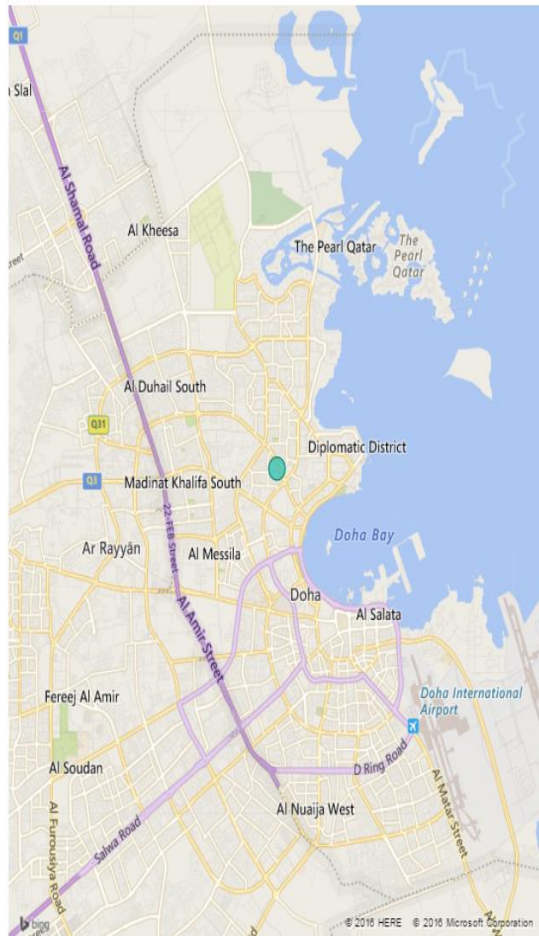- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location		Project Name	Rock Layer	Average RMR Value	Rock Grade
		Maisaed	Simsima Limestone	35	Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ■ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
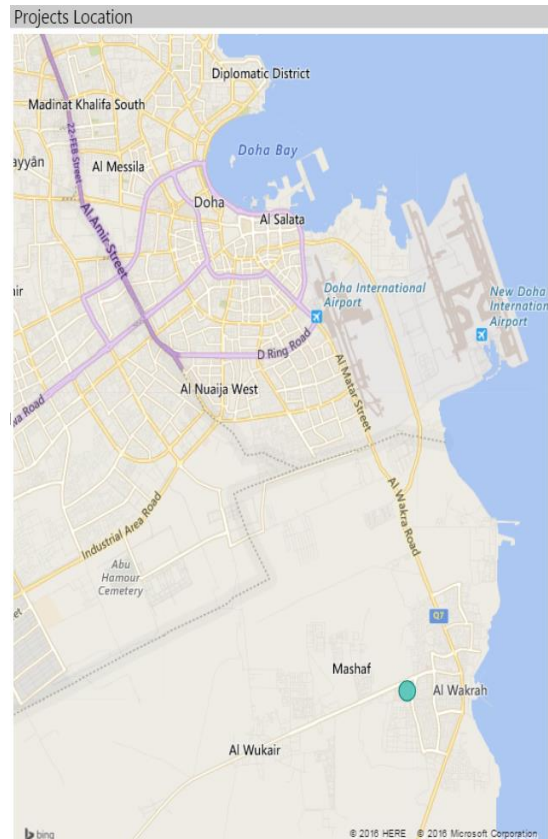- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value	Rock Grade
Mauthier South west Doha	Simsima Limestone	61	Fair to Good Rock
Mauthier South west Doha	Midra Shale	54	Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ■ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
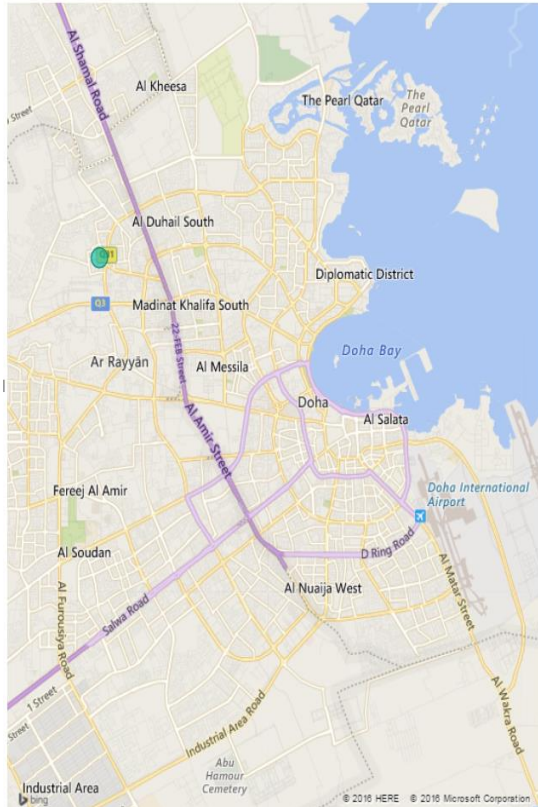- ☐ Wakrah Main Corridor
- ☐ West Al Khor

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Projects Location

Project Name	Rock Layer	Average RMR Value	Rock Grade
North East Wakrah	Simsima Limestone	27	Very Poor to Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ■ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
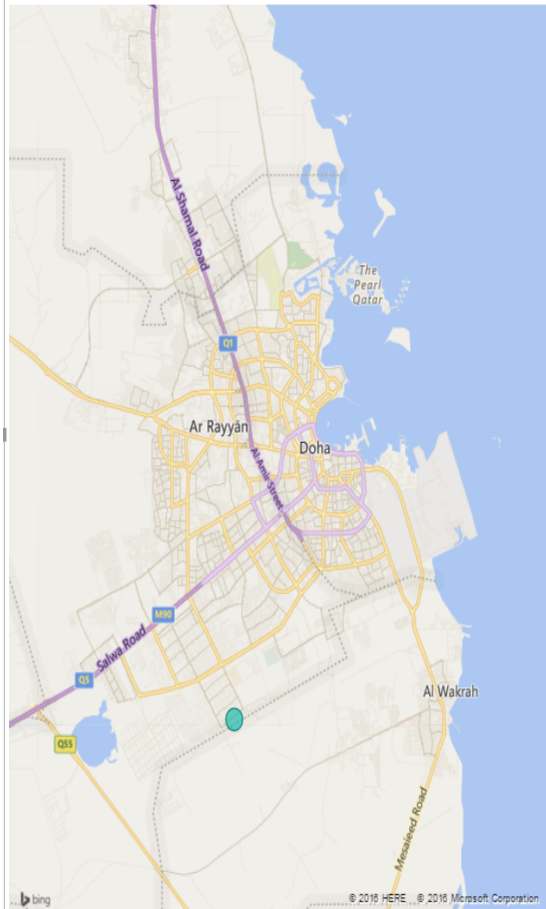- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value	Rock Grade
North Qetaifan Island	Simsima Limestone	43	Poor to Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ■ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
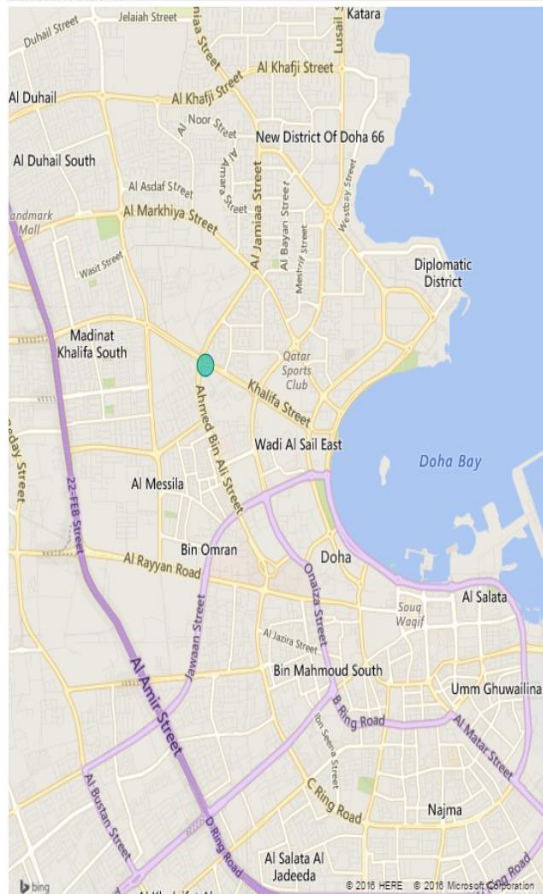- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Project Name	Rock Layer	Average RMR Value	Rock Grade
Rayyan Rd.	Midra Shale	40	Poor Rock
Rayyan Rd.	Simsima Limestone	38	Poor Rock

<

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☑ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
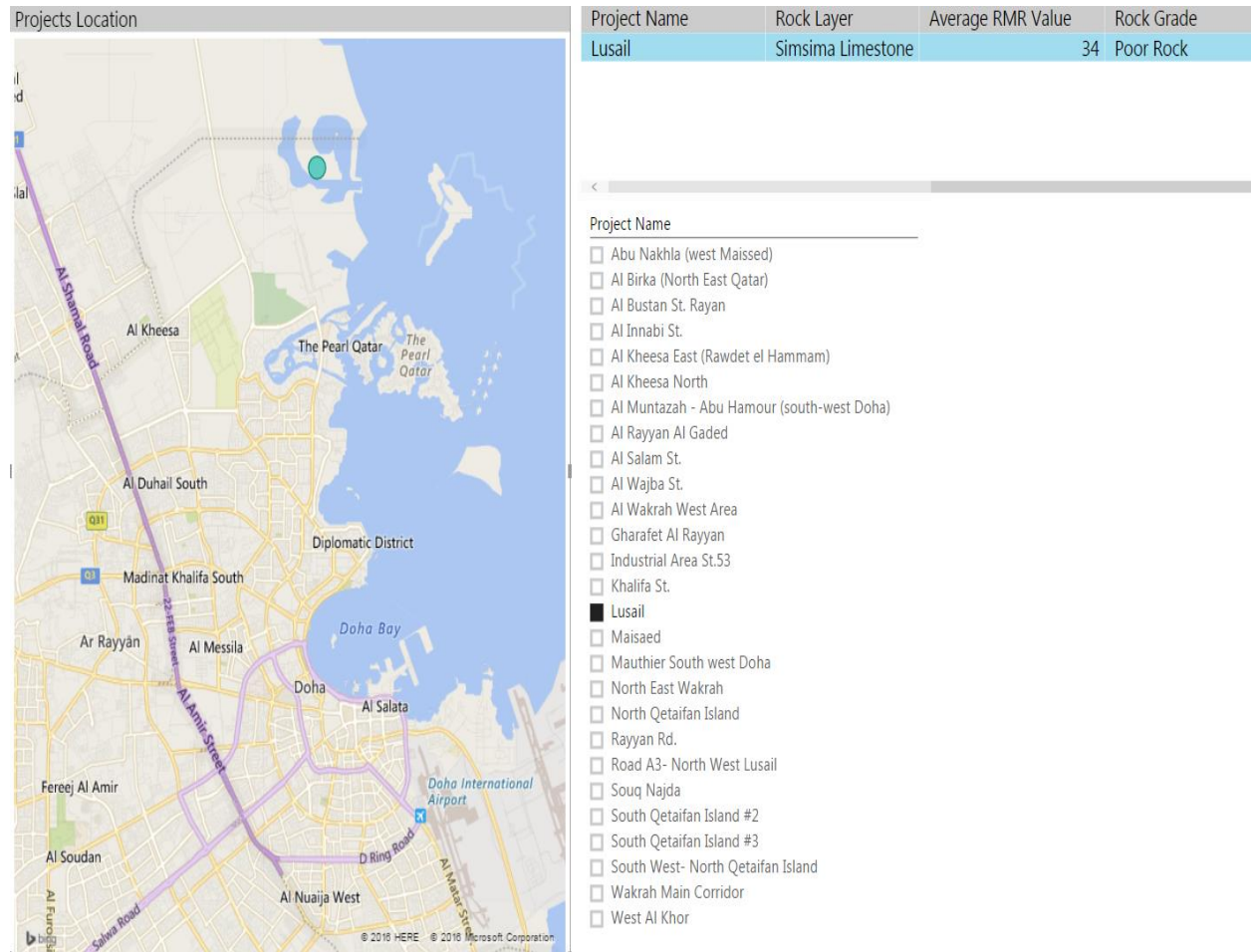- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer	Average RMR Value	Rock Grade
Road A3- North West Lusail	Rus Formation	25	Very Poor to Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ■ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
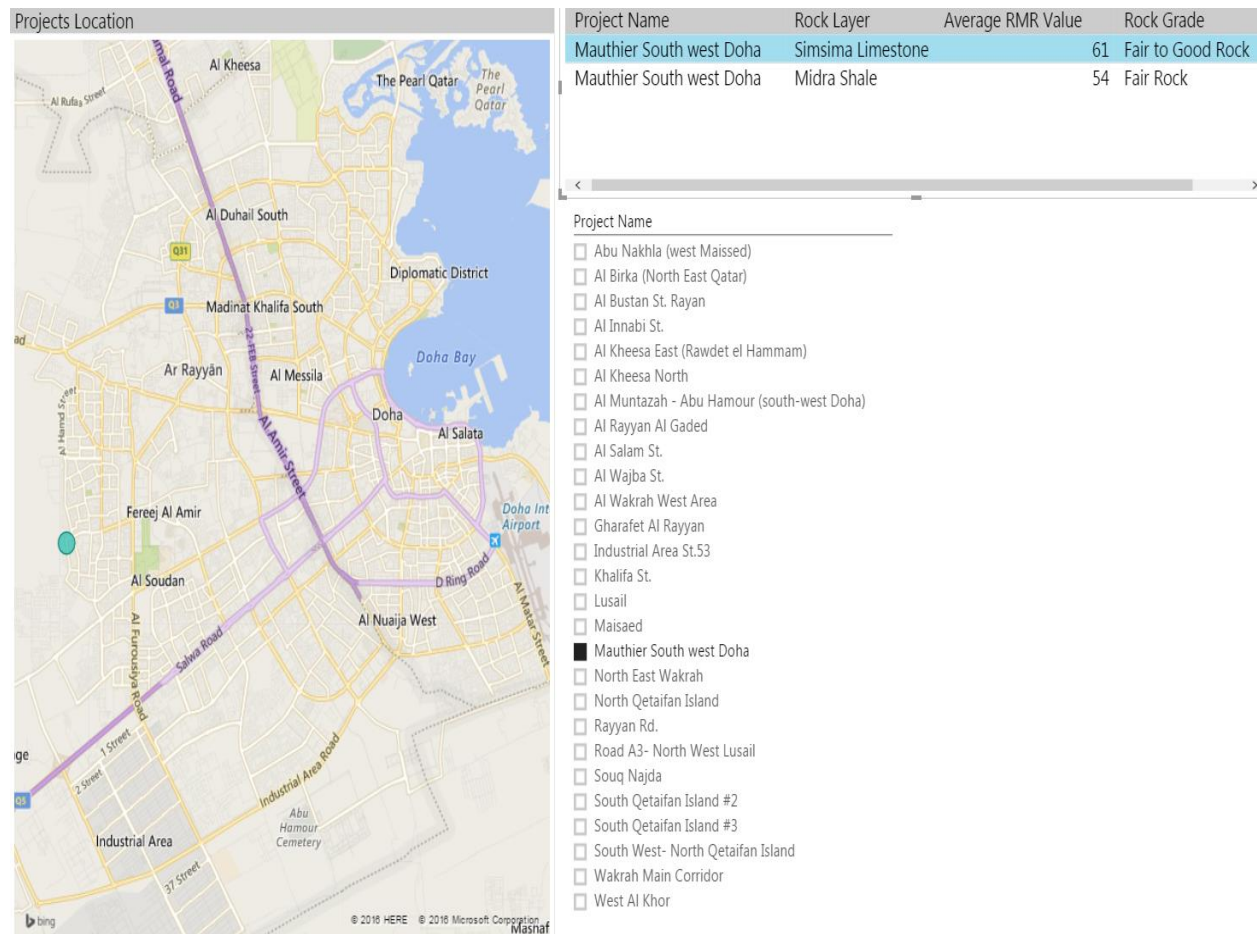- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer ▼	Average RMR Value	Rock Grade
West Al Khor	Rus Formation	34	Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
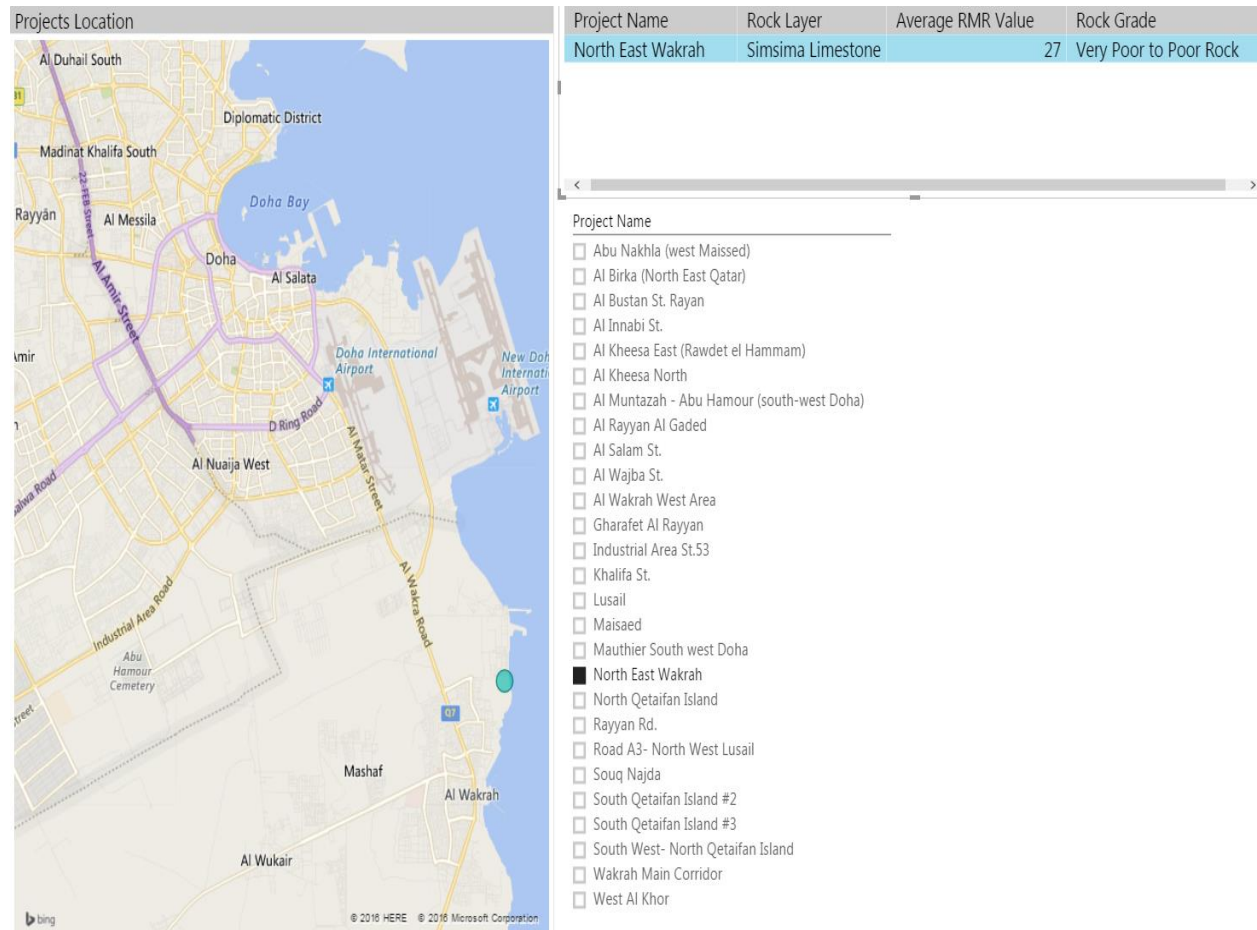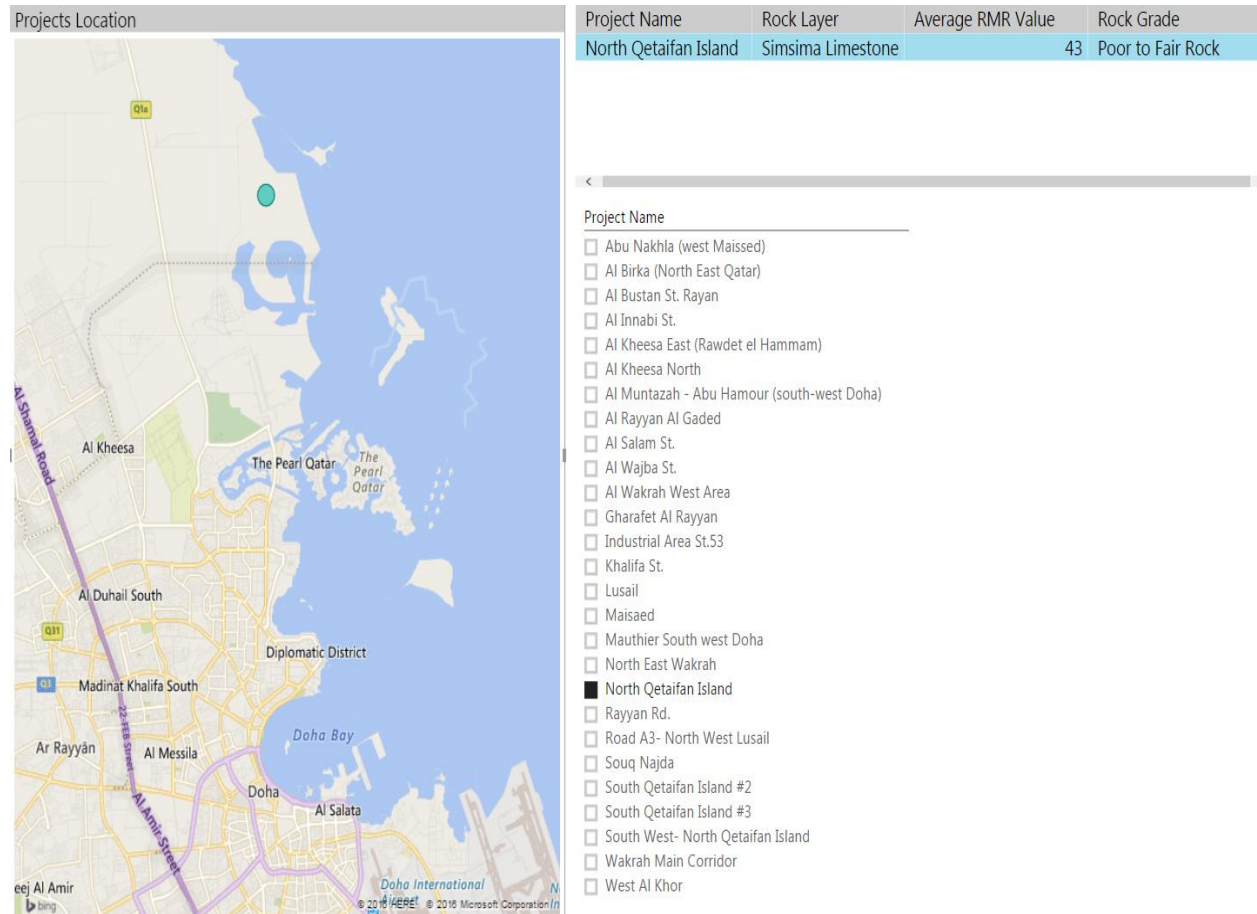- ■ West Al Khor

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Projects Location

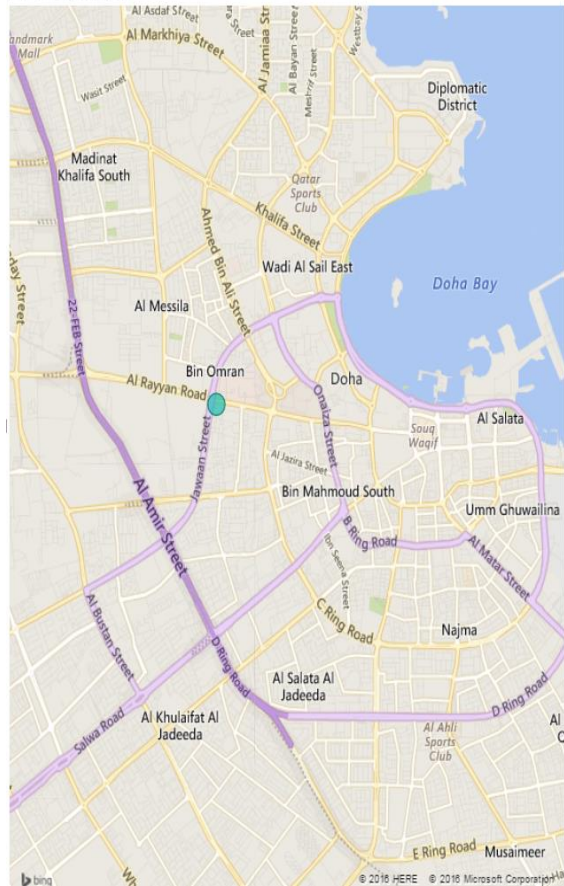| Project Name	Rock Layer	Average RMR Value	Rock Grade
Souq Najda	Simsima Limestone	48	Poor to Fair Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ■ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
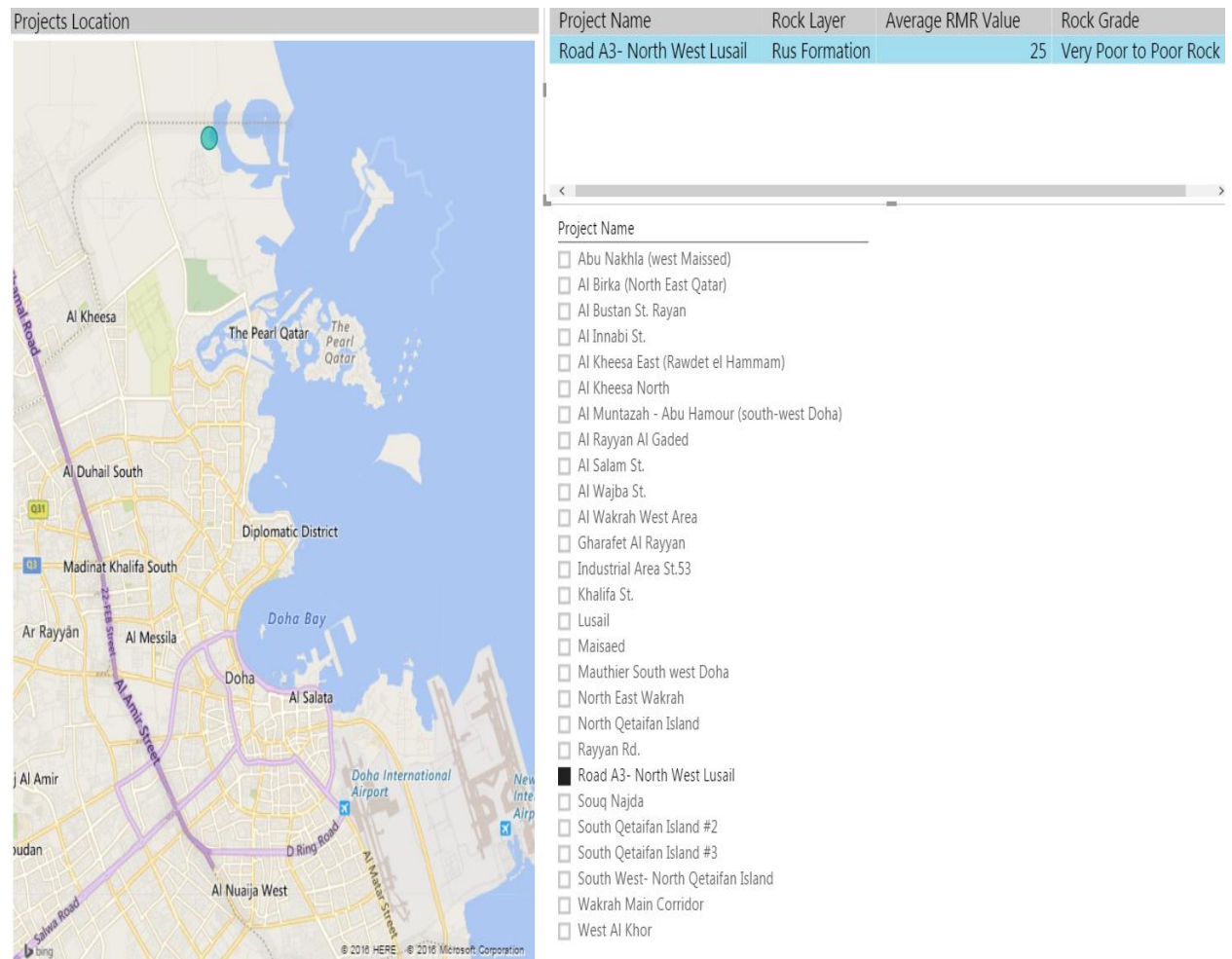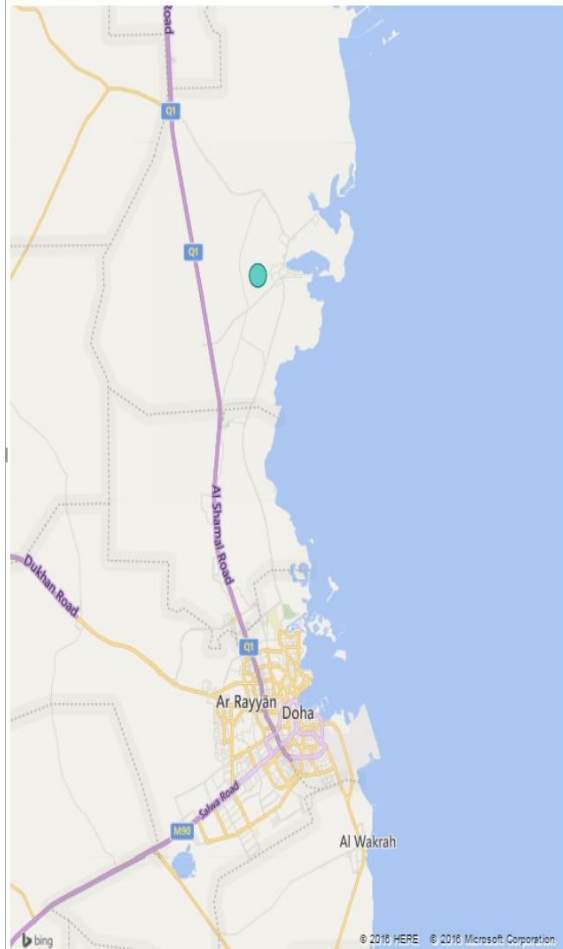- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer ▼	Average RMR Value	Rock Grade
South Qetaifan Island #2	Simsima Limestone	19	Very Poor Rock
South Qetaifan Island #2	Rus Formation	21	Very Poor to Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☑ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
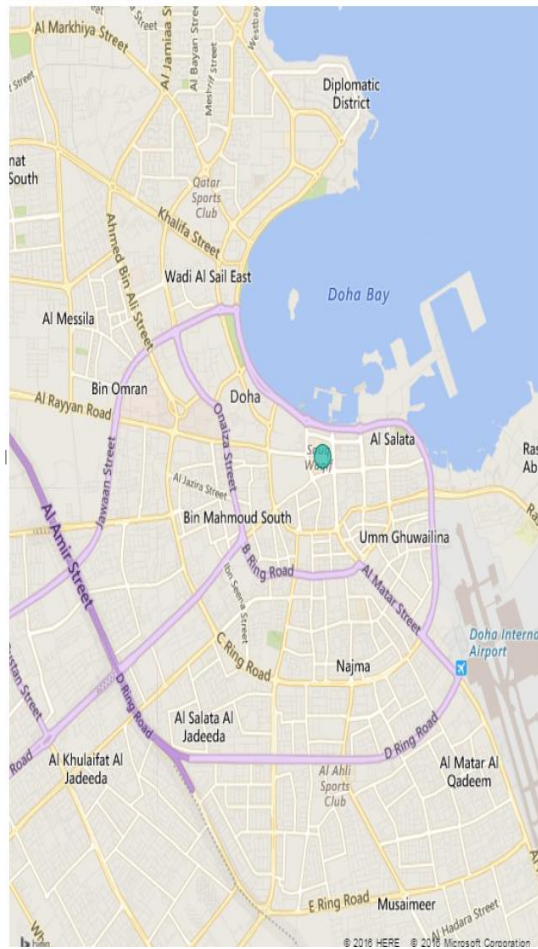- ☐ Wakrah Main Corridor
- ☐ West Al Khor

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Projects Location

Project Name	Rock Layer ▼	Average RMR Value	Rock Grade
South Qetaifan Island #3	Simsima Limestone	45	Poor to Fair Rock
South Qetaifan Island #3	Midra Shale	25	Very Poor to Poor Rock

Project Name

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ☐ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ■ South Qetaifan Island #3
- ☐ South West- North Qetaifan Island
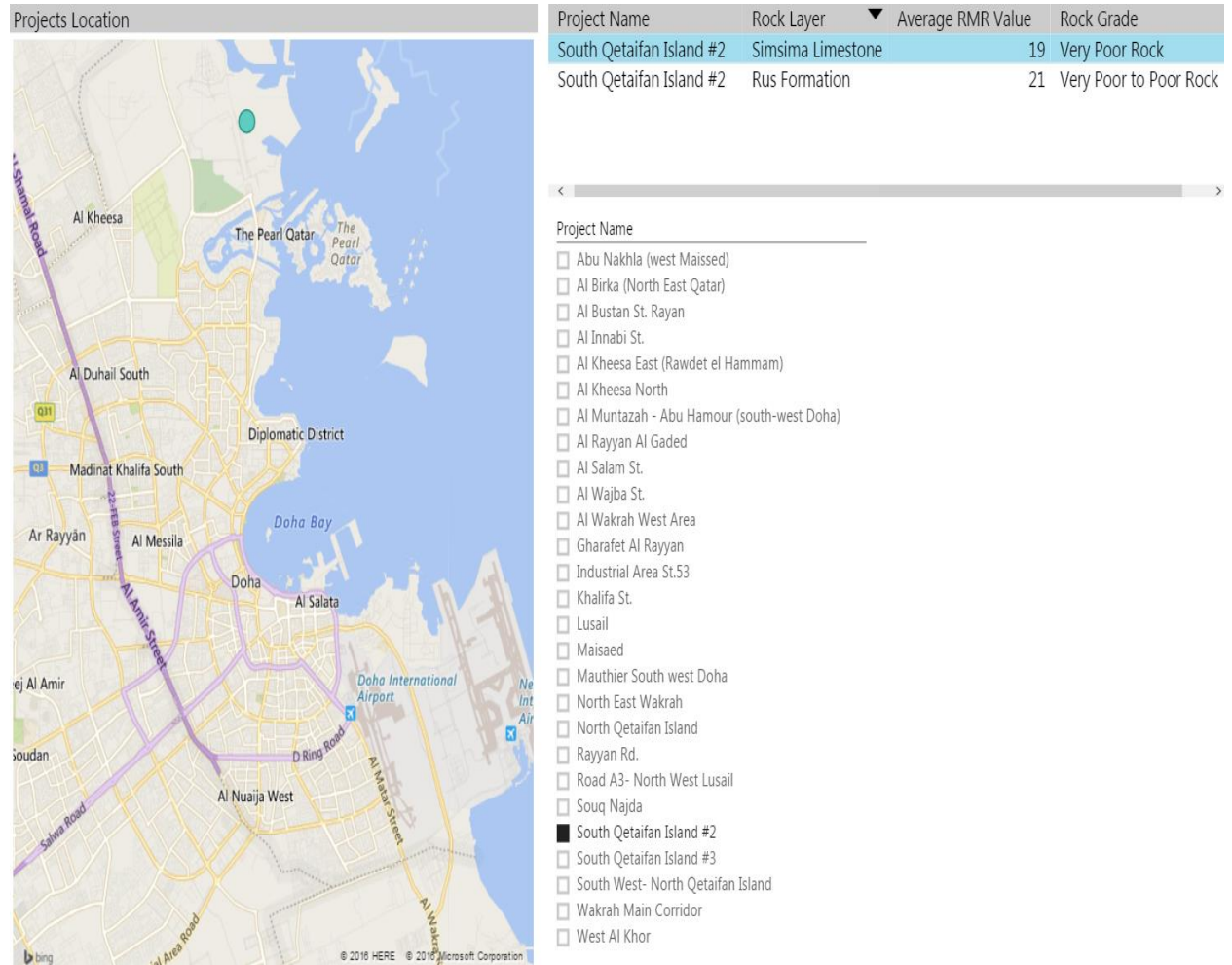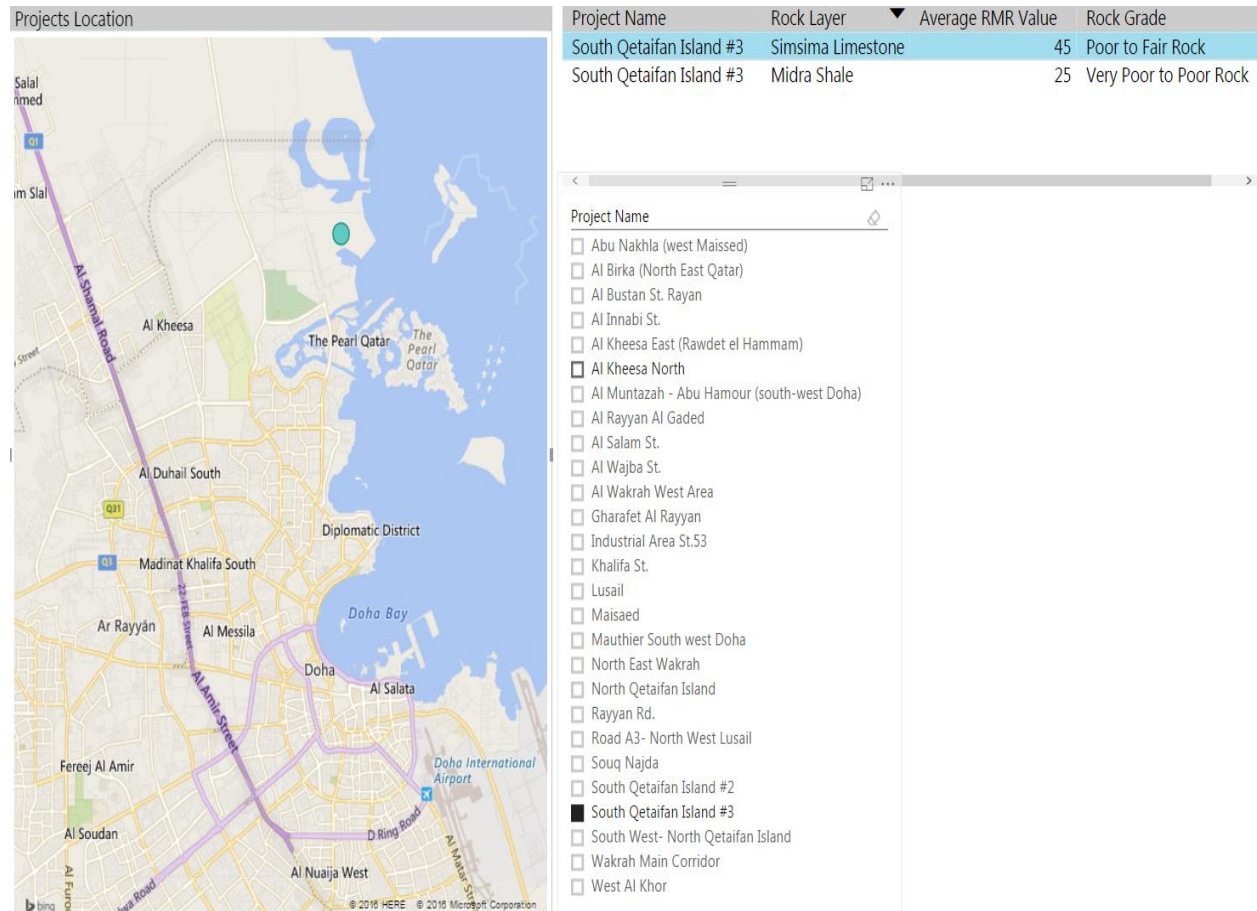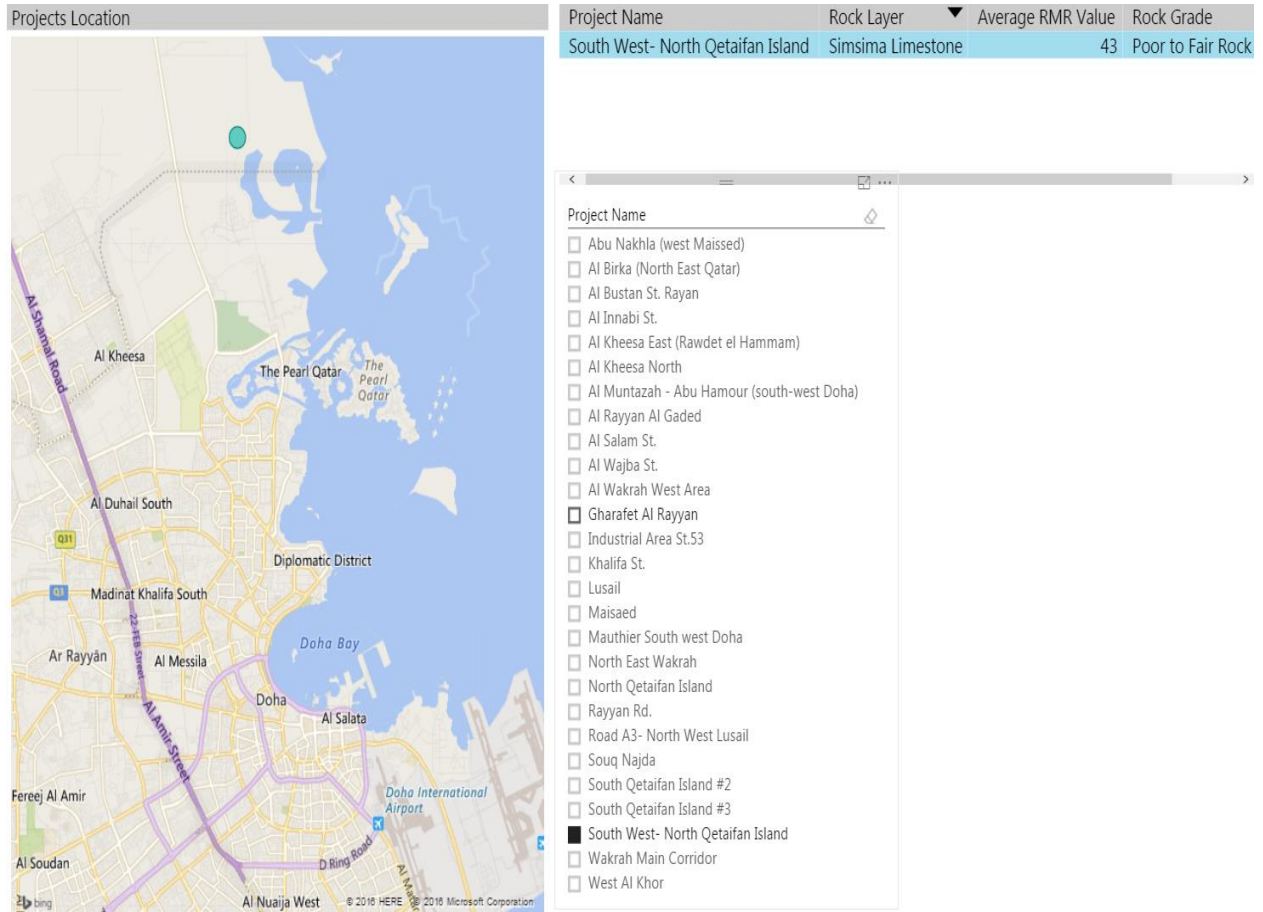- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Projects Location

Project Name	Rock Layer ▼	Average RMR Value	Rock Grade
South West- North Qetaifan Island	Simsima Limestone	43	Poor to Fair Rock

Project Name ◇

- ☐ Abu Nakhla (west Maissed)
- ☐ Al Birka (North East Qatar)
- ☐ Al Bustan St. Rayan
- ☐ Al Innabi St.
- ☐ Al Kheesa East (Rawdet el Hammam)
- ☐ Al Kheesa North
- ☐ Al Muntazah - Abu Hamour (south-west Doha)
- ☐ Al Rayyan Al Gaded
- ☐ Al Salam St.
- ☐ Al Wajba St.
- ☐ Al Wakrah West Area
- ◼ Gharafet Al Rayyan
- ☐ Industrial Area St.53
- ☐ Khalifa St.
- ☐ Lusail
- ☐ Maisaed
- ☐ Mauthier South west Doha
- ☐ North East Wakrah
- ☐ North Qetaifan Island
- ☐ Rayyan Rd.
- ☐ Road A3- North West Lusail
- ☐ Souq Najda
- ☐ South Qetaifan Island #2
- ☐ South Qetaifan Island #3
- ◼ South West- North Qetaifan Island
- ☐ Wakrah Main Corridor
- ☐ West Al Khor

Appendix -B

<u>Excavation Questionnaire</u>

Date:

- Section A

    o Respondent Name:

    o Title:

    o Years of experience:

- Section B

    o Project Name:

    o Location:

    o Scope of work:

    o Expected date of completion

    o % of finished works:

- Section C

    o Average productivity:

    o Equipment used:

    o What are the problems caused by the existed rocks?

----

    o Average excavation Depth:

    o Excavation method and sequences:

    o Average working hours:

Thank you.

Tunneling Questionnaire

Date:

- Section A

    o Respondent Name:

    o Title:

    o Years of experience:

- Section B

    o Project Name:

    o Location:

    o Scope of work:

    o Expected date of completion

    o % of finished works:

- Section C

    o Average productivity:

    o Equipment used:

    o What are the problems caused by the existed rocks?

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    o Machine\Machines diameters:

    o Cutting head type:

    o Cutting disks replacement intervals:

    o Average Tunnel depth:

    o Average working hours:

Thank you.