Politecnico di Torino

Master's Degree Thesis

"Evaluation of the condition for the advanced distance based on the correlation between Disc Cutter Load Monitoring sensor data and TBM parameters"

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Table of Contents

List of Figures

List of Tables

Chapter 1

1 Introduction

In the modern world, due to the endless surface constructions, the existing areas have reached their limits, inducing the intricacy, especially in urban areas. However, the presence of the complementary technology and experience that is capable of establishing space-saving infrastructures reduces this apprehension. In this respect, tunnels with fast and powerful transportation opportunities that do not disturb the rhythm of the cities are the ideal option.

Throughout the tunneling history, many tunnel construction methods have been addressed; however, owing to their advantages and high-performance rates, the mechanized tunneling systems have become the industry's pioneer. The most considerable contribution to the tunnel construction has been made by the Tunnel Boring Machine (TBM), which is an essential part of the mechanized tunneling industry. The ability to be designed according to the desired tunnel diameter, progress in almost all geological environments, safe, fast and continuous tunneling, and most importantly, the least demand for the workforce are the features that make TBM unique. Over time, these advantages have increased with the development of technology, and TBMs have become usable in almost all geological conditions. However, ground conditions not encountered before also led to an increase in the number of problems requiring new TBM designs and the application of new individual technologies.

In recent years, a great deal of experience has been gained in TBM tunneling thanks to manufacturers, research centers and real tunnel projects. This advancement has allowed us to push the limits of existing technology so that new TBMs, and systems developed that contribute to their operation. For instance, in 2015, Herrenknecht AG produced the new Variable Density TBM for use in the Klang Valley MRT project in Malaysia. In this project, geology, which was the prime challenge for the construction company, mainly consisted of karts limestone, including fissures and crevices. Despite the Slurry TBM had been proposed based on the ground condition, the available geology had a high risk of slurry leakage to the surface. Therefore, with a request of construction company, German manufacturer developed a new TBM that had four different operation modes and utilized more dense support medium (K, 2016) (Duhme R., n.d.).

In addition to the general TBM development, implementing individual innovations in the TBM operation has minimized the risks and provided control of specific TBM parameters. Among these innovations, the most noticeable was the sensor systems integrated into TBM. In the past, it was done manually to monitor the machine's operability and troubleshoot any problems, but today's technology especially sensors, offer the opportunity to control all machine parameters and corresponding data from a single cabin. For instance, ISP (Integrated Seismic Prediction) and SSP (Sonic Soft ground Probing) are very effective in identifying potential hazards in hard rock (ISP) and soft ground conditions (SSP). The main advantages of these devices are their workability parallel to the TBM operation that provides continuous tunneling.

Moreover, Disc Cutter Rotation Monitoring (DCRM) and Disc Cutter Load Monitoring (DCLM) systems are widely used technology in TBM tunneling. DCRM has been designed to optimize the maintenance interval of disc cutters. The utilization of DCRM increases tunneling efficiency as it reduces the frequency of manual inspection. DCRM system can also continuously control the temperature and rotation in the disc cutter. DCLM system has been established in order to monitor the cutting force in real-time. The amount of the force applied to each tool fluctuates during the advancement. The factors influencing this variation are the mixed geological condition, the position of the tools, and cutter wear that mainly form due to excessive load. The absolute adjustment of forces boosts the performance rate of TBM and reduce spending. Therefore, the DCLM system assists to the TBM driver as a controller of the applied force. Another output of this system is the opportunity to recognize the geology of the excavation face.

According to this research, the DCLM system may also contribute to determining the geological condition for the completed project, which is a crucial parameter in tunneling.

1.1 Problem Statement

The first and fundamental phase of the tunnel project is ground modeling which, starts with a desk study on local geology and continues with detailed ground investigation activities. Ground investigation works are of great importance as it is the main factor that determines investment and operating cost, tunnel alignment, the tunnel cross-section, and construction method. The parameters determined during the investigations are divided into three groups: geological, hydrogeological, geomorphological (Association, 2015). In addition, based on the data obtained, it becomes possible to predict most of the risks and to take preventive measures or to design the project in a way to reduce the impact of the risks.

During the ground investigation, gathering accurate geological data play a significant role in cost determination, risk control, and project design. However, current GI activities are not able to define the 100% correct geological model due to its constraints and complexity of ground. Hence, differences appear between the geological model developed based on the real soil parameters during the construction and the model developed based on the site investigation. These differences may increase project costs, change the alignment and general structure of the tunnel, and create new risks. Therefore, it is crucial to create a final geological model for the completed sections of the tunnel. This model is especially valuable for construction companies in terms of the difficulties that may be encountered and the extra costs these difficulties will cause.

Another importance of the perfect geological model is its inclusion in the BIM documents. In modern tunnel projects, instead of using individual software, all parties are able to work on the same database thanks to the application of Building Information Model (BIM). This digital documentation indicates the details of all the stages of the construction and allows both client and construction companies to see the lifecycle of construction and the flow of the project (Daller.J, 2016) (R., n.d.).

In this research, the DCLM system's applicability (Herrenknecht AG) in ground modeling for the completed sections of the tunnel will be examined.

1.2 Objectives of the Thesis

This research aims to identify whether there is a correlation between DCLM and TBM parameters, and based on this approach, establishing a geological model for the completed parts of the tunnel. The main input parameters will be the Angle, Id, Load from DCLM, and Thrust Force, Advance Speed, Penetration, Torque, Main Drive Speed from TBM. Analyzes will begin with visual correlation, where the main goal is to identify visual similarities between two sets of data and reduce the amount of input data for further steps. Graphs will be plotted based on Chainage - Load and Chainage -TBM parameters. Then, the statistical correlation will be realized for the parameters selected in the visual correlation stage. In this context, SPSS will be the main tool to conduct a linear regression analysis. Since no research has been conducted for the connection between DCLM sensors and TBM parameters before, the main target of this project is to determine whether there is a connection between 2 groups of data in general. If the expected results are obtained, the next step will be to create the three and two-dimensional models. The main goal in the modeling is to create a 3D model of the path followed by each DCLM sensor and compare the model with the geological cross-section of the already excavated parts of the tunnel.

The following steps will be taken in order to achieve a described objective:

- Visual Correlation
- Statistical Correlation
- 3D modelling of all tracks
- Conversion of the 3D model to the 2D model

- Comparison of the geological cross-section with newly established 2D load distribution model.

1.3 Structure of Thesis

The current thesis is designed to provide a logical sequence for reviewing issues and developing solutions. The first chapter encompasses a brief introduction to mechanized tunneling, the importance of considered research topic.

Chapter 2 shows the history of the mechanized tunneling, the evolution of the Tunnel Boring Machine, the different types of TBM, and their details, such as the application, working principle, and main parts.

Chapter 3 illustrates the current real-time monitoring systems, their objectives and applications.

Chapter 4 describes the first and current Disc Cutter Load Monitoring system, its operation for different TBMs, benefits, limitations and further developments.

Chapter 5 covers the project details include ground investigation activities, the regional and tunnel route geology, possible challenges associated with the ground, and employed TBM.

Chapter 6 present the both visual and mathematical regression analysis, the processing of data, 3D and 2D modelling of Disc Cutter Load Monitoring data.

Chapter 7 discuss the obtained results, compare the real geological profile with the obtained 2D model, the reasons for partial success of research and further possibilities.

Chapter 2

2 Literature Review on Tunnel Boring Machine

Utilization of tunnels for watering purposes by Babylonians or for establishing marshes by Greeks and Romans, and all such historical examples evidence that tunnels have always been a medium to facilitate living conditions (Britannica, 1957). Although these structures still play the same role in the modern world, there are various contrasts between the new and old tunnel industry in terms of construction methods and intended use. Tunnels were appropriated for mining, military, and agricultural purposes until the 17th century, but technological developments after the 19th century initiated the fabrication of transportation tunnels (Britannica, 2019). Especially, the advancement of the industry in the 1800s and the rapid increase in the human population precipitated the need for a large number of tunnels (B.Maidl, 2008). In this sense, the tunnel constructed under the Thames river in England, which connected Rotherhithe and Wapping, could be a good instance. The main objective of this project was to simplify the transportation problem for that period. This structure can be seen as the first shield used project, but the main purpose of the shield designed by Mark Isambard Brunnel was to create a secure working condition for employees (King.J, 2000) Figure 2-1.

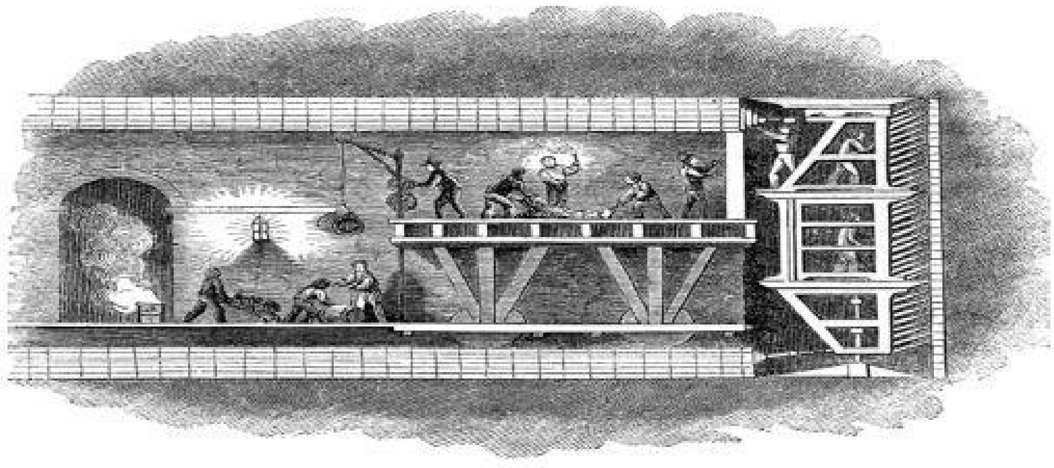

Figure 2-1 Tunnel construction by using M.S Brunnel's shield

In the following years, many new machines were manufactured; however, the most notable one was the model designed by Germain Sommeiller, which used successfully for tunnel construction between France and Italy in 1857 (King.J, 2000).

Another successful production was the design of two American soldiers, Frederic Edward Blackett Beaumont and Thomas English, which succeed in the Channel Tunnel project in 1881-82. The parent feature that distinguished this machine from previous models was its capability to excavate in soft ground.

In 1846, Henri Joseph Maus developed the first tunneling machine in Belgium (L.David, 2016) (Figure 2-2) This machine was not considered as a type of TBM since it did not excavate full face with available tools. In addition, the high price and the economic crises of that period caused Henri's model to disappear in a short time. Between 1851 and 1856, American engineer Charles Wilson built and patented the new tunneling machine (Figure 2-3) (B.Maidl, 2013). According to the results obtained from the test in the Hoosac tunnel, the machine was not capable of competing with the drilling and blasting method. After Charles, many attempts have been made to manufacture new machinery in various parts of the world; however, most of them either could not pass the outcome of the Charles model or completely failed (King.J, 2000).

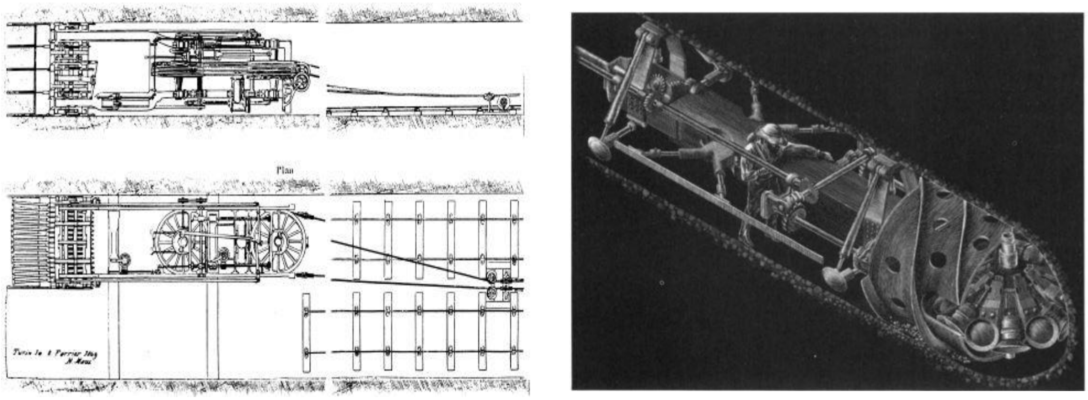

Figure 2-2 Henri's model (left) and Charle's model (right

All these and similar initiatives and researches made in the past are the essential sources of formation and development of the existing mechanized tunneling industry. Particularly, the construction of first open gripper TBM by Robbins in the 1950s was a new era for tunneling (Figure 2-5). In the first project, Robbins' machine proved its economic suitability by showing that it could meet the desired distance using only the disc cutter. Later, European countries such as the UK and Germany started to produce their local TBMs and cooperated with different countries. In particular, the double shield concept created by Carlo Grandori in collaboration with Robbins in the 1970s, which proved to be applicable in the complex formation in the Silo tunnel (C.Grandori, 1976). Since then, the tunnel industry has consistently experienced new machines and technologies. For instance, starting the micro tunneling in the mid-80s (M.Herrenknecht, 1991), then the construction of the first multi-head shield by the Japanese and Robbins (Telford, 1992), or the first use of foam for EPB soil conditioning in Europe (P.Marcheselli, 1994)

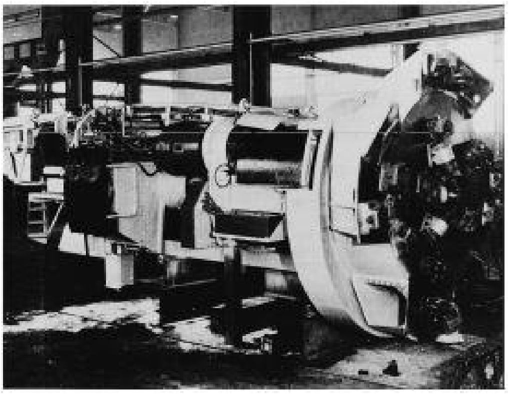
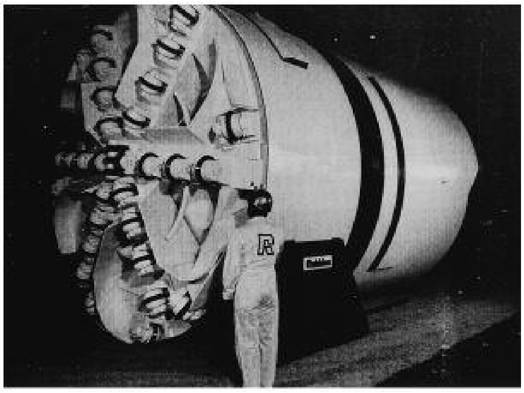

Figure 2-3 The first modern Gripper TBM (left) and Double Shield TBM Robbins (Right)

Looking back, it can be perceived that there are hundreds of achievements and failures behind the current high-level mechanized tunnel industry. In the past, due to lack of technology and experience, tunnels were used only for limited purposes, while today's technology is able to produce TBMs even capable of operating beyond the boundaries of Earth (J.Rostami. C.Dreyer, 2018) (C.S.Allen, 1988) (J. Rostami, 2019)

2.1 Tunnel Boring Machine (TBM)

Compared to the past, the cities are now more crowded, but the most vital advantage of the modern world is the presence of technology and experience, which allow building infrastructures that can manage this commotion. The most blatant instance of these infrastructures is the tunnels that play a prominent role not only in human life but also in different industry sectors. However, the tunnel projects are labyrinthically enough as they require a lot of experience, finance, and construction time. In this sense, the correct machine selection and its management, which cover all aspects of construction, is considered as a basis of being successful in the projects where TBM is utilized. There are specific parameters that influence TBM choice; however, the main are geological and geotechnical conditions (*Figure 2-4*).

Hard Rock	Soft Ground	Variable Geology	Fractured Rock	Fractured rock (with water)
Gripper TBM	EPB or Slurry TBM	Mixshield TBM	Double Shield	Single Shield

Figure 2-4 Different geological conditions and the most suitable Tunnel Boring Machines

Improved health and safety conditions for the workers, the possibility of crossing complex geological conditions, less environmental impact, good quality of the final product, and higher advance rate are the main advantages that make TBM unique. In addition to these benefits, there are some limitations such as incompatibility in tunnel projects shorter than 1 km, long installation time, high investment costs, limited adaptation in very mixed conditions, and high logistics demand (Tunneling, n.d.). The main peculiarity of TBM tunneling that allows it to overcome conventional tunneling is reduced working time.

The TBMs consist of 2 large groups to be employed in hard rock and soft soil. The first group, including Gripper, Single Shield, and Double Shield, is typically utilized in hard rock environments where there is a risk of water ingress.

The soft ground tunneling is usually held in urban areas where the main target is to build a tunnel with minimal subsidence effect on the surface, especially in areas with a significant amount of surface structures. In soft ground environments, the soil has a low self-bearing capacity, and therefore the ground may collapse to the machine during the advance, which will cause the surface to subsidence. Also, if the construction takes place under the water table, the low permeability of the soil creates problems with the water inlet and water pressure (Chapman D. N., 2017). In this context, Slurry and EPB TBMs are the most effective machines since they own face support system that overcomes all the stated problems (Maidl, 2014) (Chapman D. N., 2017).

2.2 Tunnel boring machine without shield

2.2.1 Gripper TBM

The ideal condition to run Open or Gripper TBMs (Figure 2-5) is medium and hard rocks containing water inlet. In hard rock conditions, it is probable to encounter water and air-filled cavities along weak zones. Since the machine does not own a shield that prevents the water inlet, it is necessary to implement preventive measures such as probing, pregrounting against any groundwater-related activities (S.Kuwahara, 2000). In modern Gripper TBMs, the Integrated Seismic Prediction system (Herrenknecht AG) is used to detect potentially dangerous situations.

If, during the advancement, no regular support is needed to provide stability, this machine becomes super productive. However, when boring through fragile geological formations, different systems for prompt rock support must be assembled behind the cutterhead.

In contrast to Shielded TBMs, the utilized support systems vary based on the existing ground condition in Open TBMs. The most commonly used support devices, which are shotcrete, rock bolts, steel arches, and anchors are coming from conventional tunneling method (Maidl, 2014).

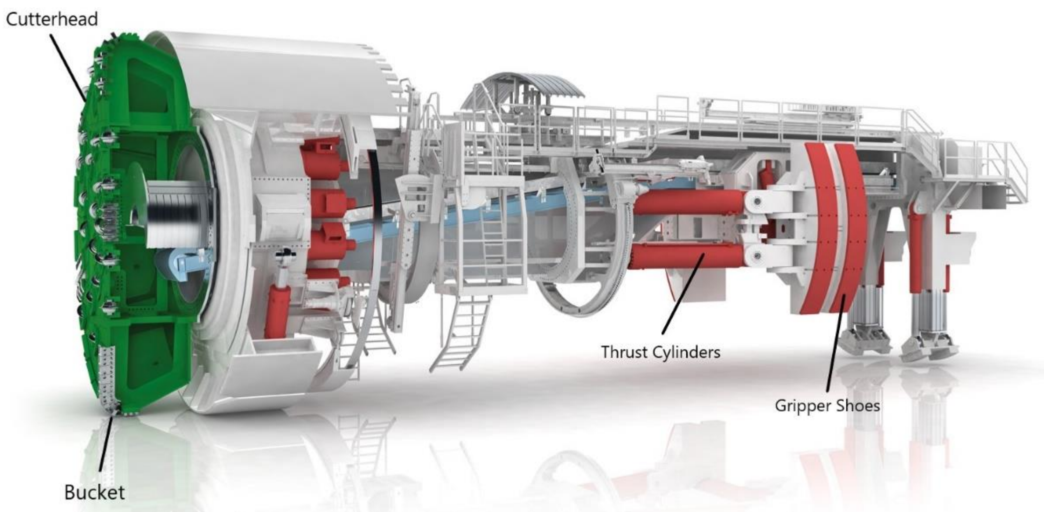

Figure 2-5 Gripper TBM (Herrenknecht AG)

The main advantages of modern Gripper TBM are (Herrenknecht):

- High and continual tunneling capacity and highly impeccable excavation in the stationary rock formation
- Preventive measures against the rock, which establish safe conditions both for machines and workers in risky zones.
- Portable partial shield allows for flexible reactions to convergences

The cutterhead of Gripper TBM mainly comprises of disc cutters, which each is exposed to a different amount of load. During the advancement, due to the contact of cutter and surface, temperature enhancement is observed. In this case, the water jet cools down the tools and also control the dust formed by excavation (Hudson.J.A, 1993). Bucket mounted at the cutterhead receives the muck formed from advancement, and then the material is transported out of the tunnel using other further transport systems, which are usually belt conveyors. The progress of the machine is mainly achieved thanks to the combination of gripper shoes, which locate on both sides of the machine, and thrust cylinder. The shoes are braced against the tunnel wall, and thrust cylinders push the cutter head against the excavation face. The working principle of Gripper TBM has been illustrated in (Figure 2-6).

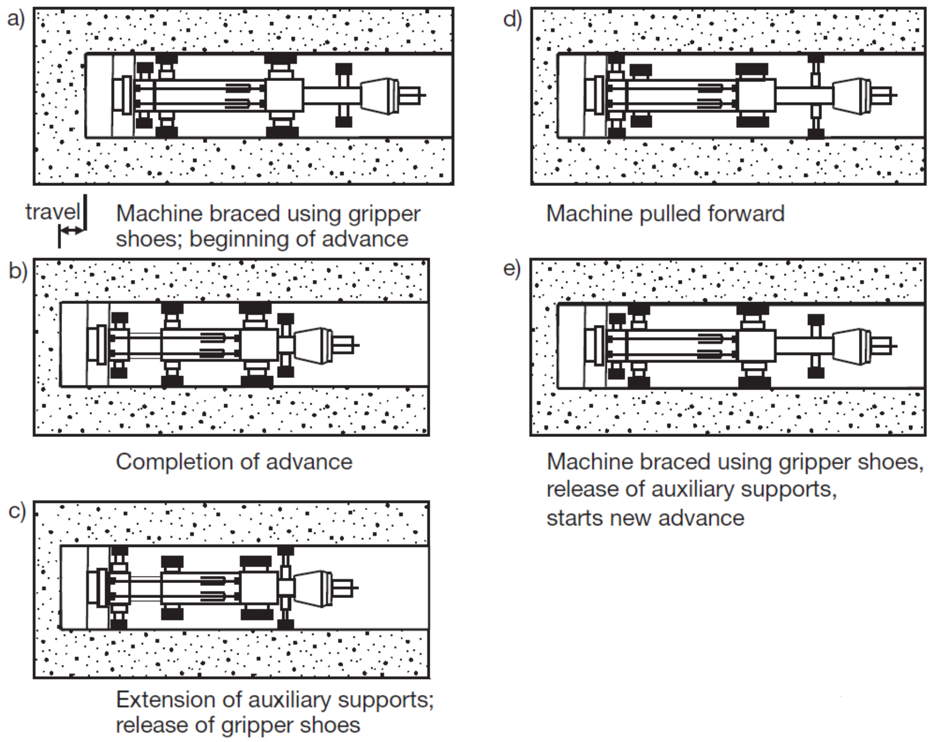

Figure 2-6 The working principle of Gripper TBM

2.3 Tunnel boring machine with shield

2.3.1 Single Shield TBM

The essential application area of Single shield TBMs is the soft and brittle rocks where rock collapse is highly probable (Figure 2-7). The Gripper and Single Shield TBMs have no apparent difference with regard to cutterhead, while the key differences are, the shield which guarantees the stability of rock and ensures the safety of staff and equipment, and the way which thrust is obtained in order to provide advance (B, 2008). In order to provide thrust force in single shield TBM, the segment pushing technique which will be demonstrated in the following sections is applied. The availability of the shield establishes affordable conditions to install a proper lining.

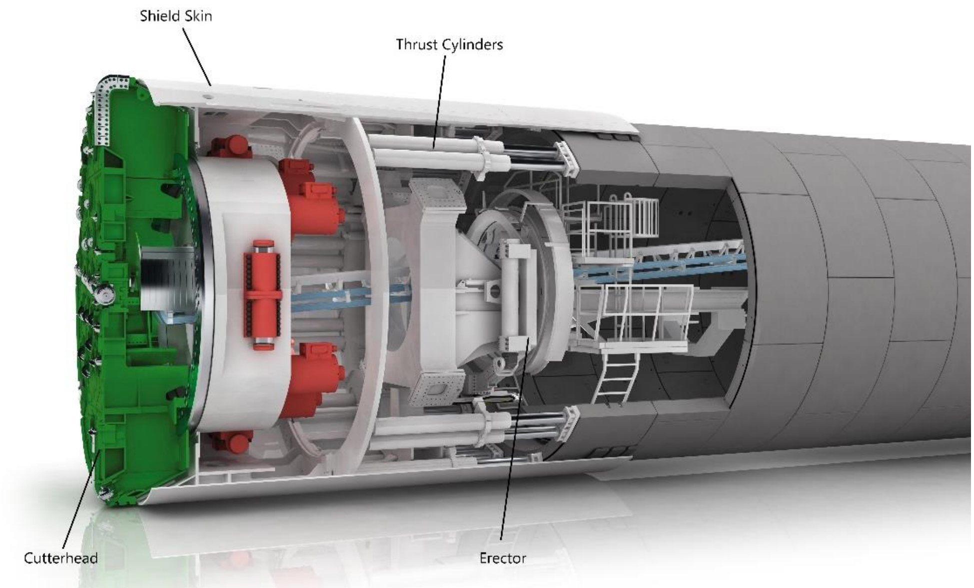

Figure 2-7 Single Shield TBM (Herrenkecnth AG)

2.3.2 Double Shield TBM

This machine is particularly suitable for the construction of long tunnels consist of hard rocks containing fault zones. Having both open and single Shield TBM's features extend the application area of Double shield TBM (Figure 2-8) (B, 2008) (Yurtaydin, 2011). Double shield TBM is more efficient than single shield TBM since it is able to bore independently of segment lining. Another benefit of this machine over a Single shield TBM is the time required for the ring installation, approximately 10-15 minutes. From the mechanical point of view, the feature that distinguishes Double

Shield from others is the presence of front and mean shield, which is attached to the telescopic jack.

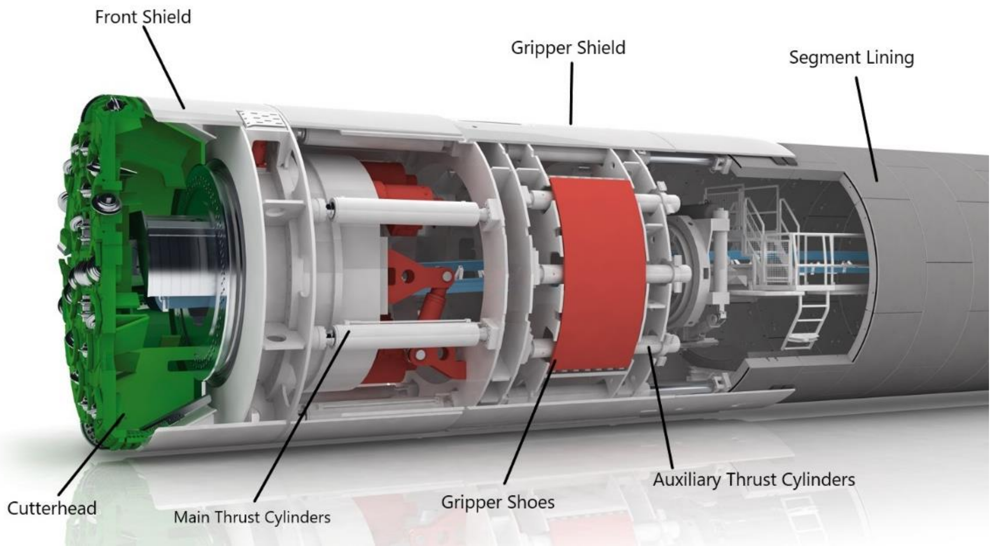

Figure 2-8 Double Shield TBM (Herrenknecht AG)

The machine has been endowed with two types of cylinders: telescopic thrust cylinders that supply the main thrust force for advancement and auxiliary cylinders to stabilize the last installed ring. Without any technical modification, Double Shield TBM provides continuous tunneling, especially in the rocky conditions without fault zones. Whenever machines encounter fault zones, telescopic connection, and main thrust cylinders completely lock their function. In this case, auxiliary cylinders begin to provide the main thrust force. Since the segment lining and tunneling are performed one by one, this type of construction is known as discontinuous tunneling. The main reason for this modification is to establish safe conditions both for machines and workers.

2.3.3 Earth Pressure Balance TBM

In soft ground tunneling, due to its successful application against excavation face and groundwater, Earth Pressure Balance TBM (Figure 2-9) is the most extensively used machine. Especially in urban tunneling, EPB is the most productive machine to refrain surface subsidence that can damage the surface structures (Guglielmetti.V, 2008). The machine's cutting wheel is equipped with special cutting tools, which are different from tools used for Hardrock TBMs. During the advancement, muck falls to the excavation chamber through the opening and mixes with already available materials. The arms in the excavation chamber and pressure bulkhead mix the materials until to reach the desired property. When the equilibrium is reached between the pressure of surrounding materials (soil, water) and the available material in the excavation chamber, the stable condition has been obtained, and the tunnel can advance continually.

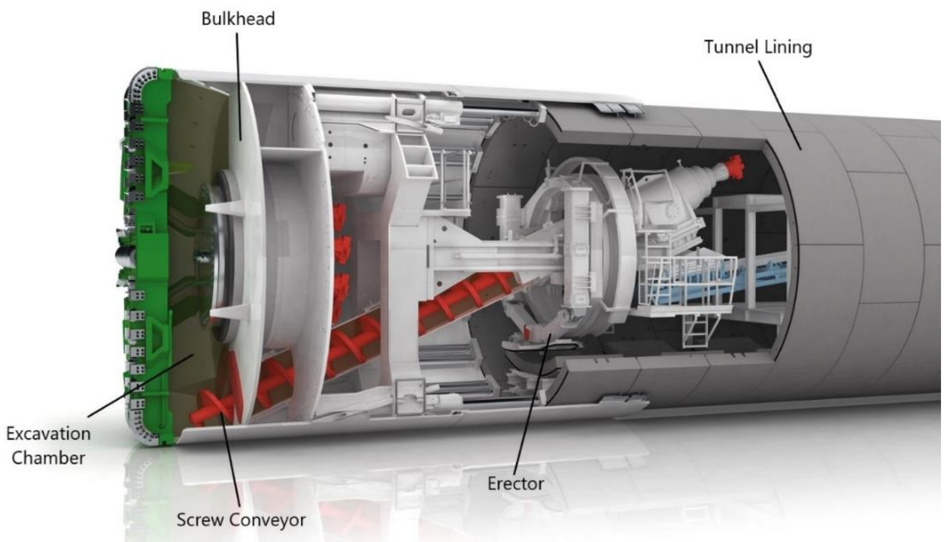

Figure 2-9 Earth Pressure Balance TBM (Herrenknecht AG)

One of the indispensable elements of EPB is the screw conveyor, which regulates the pressure and transport the material from the excavation chamber. If the screw conveyor rotates above the fixed speed limits, the amount of the excavated material will decrease in the excavation chamber, thereby the deterioration of the support pressure. Therefore, it is necessary to adjust the rotation speed properly (Yang, 2009).

The primary employment area of EPB is soils with 0.6 mm fine grains (more than 30%) (Figure 2-10). The content of the fine grains plays a considerable role in the applicability of the machine. In favorable conditions, the excavated material can be used as a support medium by adding a small amount of water. However, while the particle size increase (coarse-grained), water loses its workability, and the need for new additives emerges.

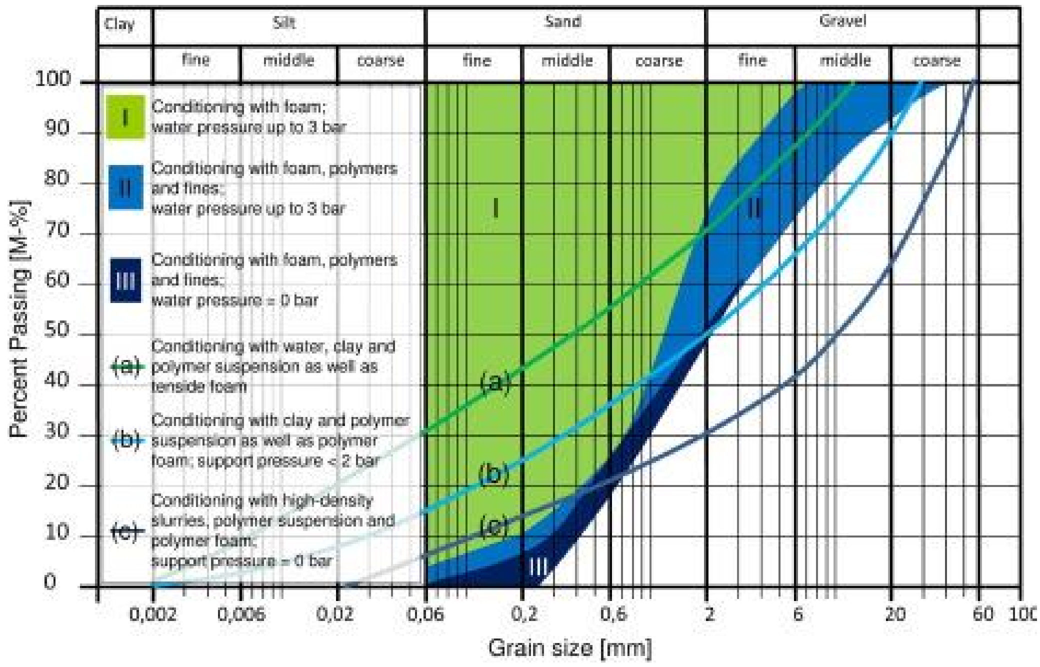

Figure 2-10 Application area of Earth Pressure Balance TBM (Budach C., 2015)

The excavated soils must have the following properties in order to be used as supporting materials:

- Pasty to a soft consistency
- Low internal friction
- Low water permeability

A small quantity of soil owns these parameters; that is why special additives are applied to condition the excavated material. The most commonly used are foam, bentonite, clay, or simply water (Budach C., 2015).

Based on different transportation and face support options, EPB has different operation modes (Figure 2-11).

Open mode - In the case of stability, it is not essential to apply face pressure to the tunnel face, which means that the EPB can advance in open mode. In this mode of operation, unlike classical EPB principles, the excavation chamber is empty. The excavated material is transported directly by screw conveyor after falling from the opening. Also, access to the excavation chamber becomes easier for workers (Galli.M, 2016) (Herrenknecht Martin, 2003).

Semi-closed mode - is a combination of open and closed operating modes. Typically, this mode is used for a mixed face condition. In contrast to the open mode, half of the excavation chamber is filled with muck, while the other half is filled with compressed air. As a consequence, access to the chamber is only possible from the compressed upper part. In addition, the presence of compressed air increases the efficiency of the material flow through the screw conveyor (Galli.M, 2016), (Herrenknecht Martin, 2003).

Closed mode - is the original EPB mode where urgent support is required to fix the tunnel face and minimize the collapse of the surface. In this mode, the excavation chamber is fully filled with muck, and in case of access for repair purposes, the material is lowered and replaced with compressed air. In addition the screw conveyor and cutting wheel are likely to become clogged due to the pressing of muck in the room (Galli.M, 2016), (Herrenknecht Martin, 2003).

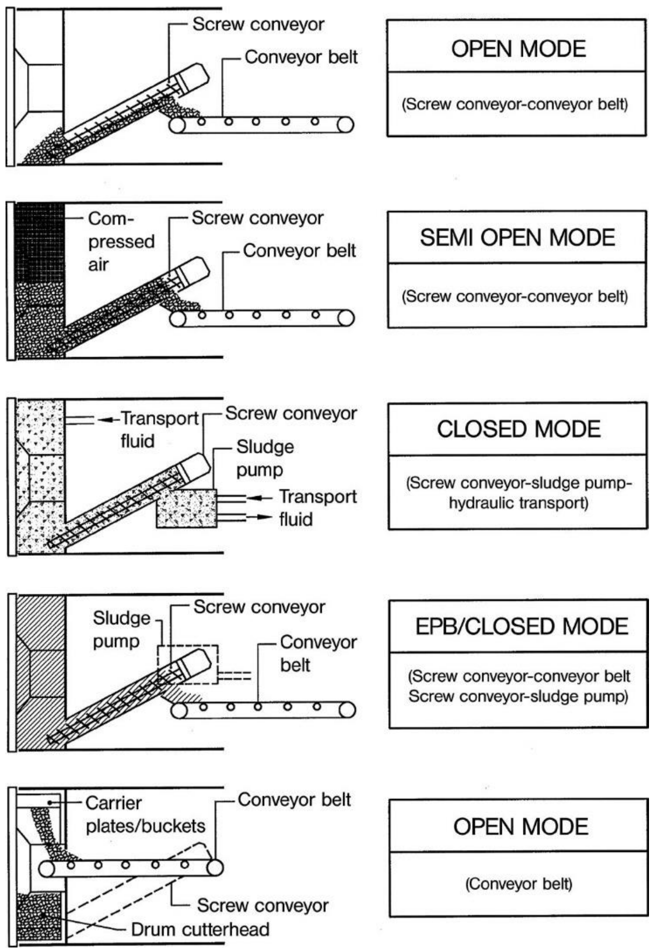

Figure 2-11 Different operation modes of Earth Pressure Balance TBM (Herrenknecht Martin, 2003)

2.3.4 Slurry TBM

One another machine with face support function is Slurry TBM. The breakthrough for the Slurry Shield TBMs occurred after introducing the first Slurry Shield TBM in Japan (1967). This machine was a prototype; however, after three years Japanese produced the first functional Slurry Shield with 7.20 meters diameter for the Keiyo tunnel project. Since that time on, these TBMs started to be used very widely in both Europe and Japan. Except for some recent technical variations, the modern Slurry Shield TBMs operate in a similar way to the Japanese model. The creation of Hydroshield TBM by Wayss Freytag in 1972 was another event that triggered the development of Slurry shielded TBMs. In the following years, thanks to the collaboration of Ways & Freytag and Herreknecht AG, the hydroshield machine developed and new Mixshield TBM was introduced to the tunneling industry (Maidl, 2013). (Figure 2-12).

Figure 2-12 MixShield TBM (1985 Hera Tunnel)(Herrenknecht Martin, 2003).

Thanks to its application in the Hera tunnel project, with a daily advancement rate of 20 meters, Mixshield TBM proved its usability and success. After this achievement, manufacturers proceeded to refine this technology, for instance, by increasing the excavation diameter, equipping the erection section with vacuum, installing electronic parts for data collection and analysis, and equipping TBM with articulate cutterhead. Consequently, in the current tunnel industry, there are two most utilized Slurry TBMs. One is the product of Japanese manufacturers, and the other belongs to the German manufacturers.

2.3.5 Mixshield TBM

The typical application environment of Mixshield TBM is made up of coarse and mixed soils (Figure 2-13). In the past, one chamber system was adopted for slurry machines; however, uncontrolled excavation of tunnel face caused density variation in the suspension. Thus, demand increased for the two-chamber system, which is available in modern Mixshield TBMs. The chambers are separated by the submerged wall, and the connection between them is carried out through the opening at the bottom of the wall. During the advancement, the excavation chamber is entirely filled with suspension, while the rear chamber is filled partially, and the upper part is exposed to compressed air. The compressed air in the bulkhead control and regulate the support on the tunnel face (Chapman D. N., 2017).

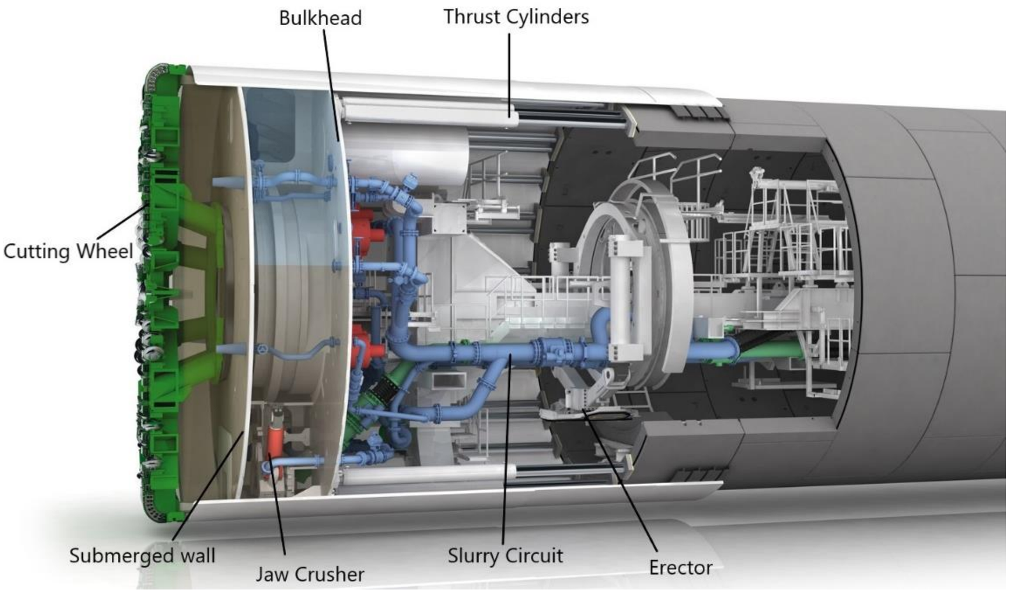

Figure 2-13 Modern Mixshield TBM (Herrenknecht AG)

Unlike the EPB TBM, the Mixshield machine utilizes pressurized fluid to guarantee the stability of the excavation face. During the advancement, the slurry coming through the pipes is tapped to the tunnel face, where it blends with the excavated material. The resulting compound is then conveyed back to the separation plant by means of slurry pipes. In the separation plant, the excavated material is taken from the mixture thanks to the sieve and cyclones. In this way, the same slurry can be utilized several times for the same objectives. The simple fluid, to use throughout the advancement, is the water, which requires the ground to include fine grains. However, if the geology involves sand or gravel, the application of slurry becomes inevitable. In this sense, the bentonite is the most used slurry, but in case of high permeable ground condition (5*10-3 m/s), the bentonite probably loses its functionality and flow to the ground. Therefore, supplementary materials can be united in order to improve bentonite properties (Maidl, 2013). Since the bentonite can transfer only certain sized particles, some fine particles in the combination of bentonite can settle both in excavation and bulkhead chamber, causing an increase in construction time and cleaning costs (Chapman D. N., 2017).

The vital part of Mixshield TBM is the separation plant that sometimes becomes a disadvantage due to lack of available space (Figure 2-14). The size and location of the separation plant vary according to the size of TBM. It could locate on the surface or in the back-up system. In addition, Since the Slurry machine is used for heterogonous conditions, the components of the separation plants must be adaptable in case of the varied ground.

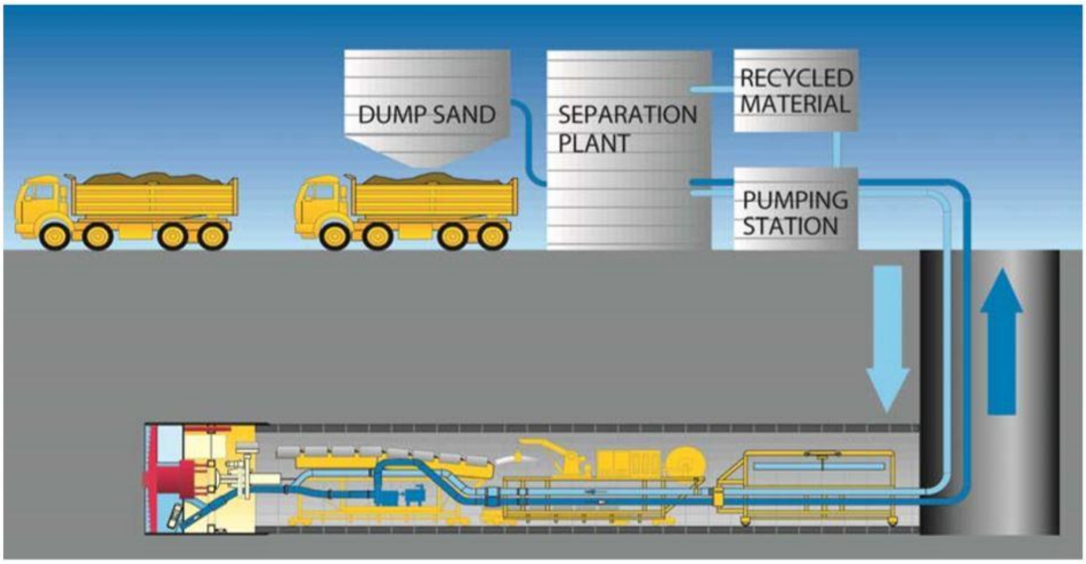

Figure 2-14 Separation Plant (Herrenknecht AG)

Modern Mixshield machines are able to advance through complex formations under high pressure. Since the large boulder is likely to encounter in heterogeneous ground conditions, Mixshield is equipped with a jaw or drum crusher (Figure 2-15), which enhances its application area.

Figure 2-15 Jaw crusher (left) and Drum crusher (right)

2.4 The Main Parts of TBM

Although the selection of TBM according to the actual ground, is a critical parameter, the proper design of the individual parts of the machine is also essential for the successful tunnel project. TBMs are mainly made up of three main components. These, the cutterhead, which is designed based on the existing ground condition to be excavated, are the power units for the advancement and rotation, and other auxiliary equipment. Detailed information about the parts of TBM will be given in the following sections.

2.4.1 Cutterhead

According to (Rostami J., 2017), the cutterhead (Figure 2-16) is the most critical element of TBM since it influences the efficiency of cutting, the balance of the head, the life of the cutters, the maintenance of the main bearing/gearbox, and the effectiveness of muck transfer. By considering all these functions, (Rostami J., 2017) has stated specific steps that need to be realized, such as cutter selection, cutter location and spacing, the shape of the cutterhead, cutterhead profile, cutter distribution on cutterhead, and muck buckets.

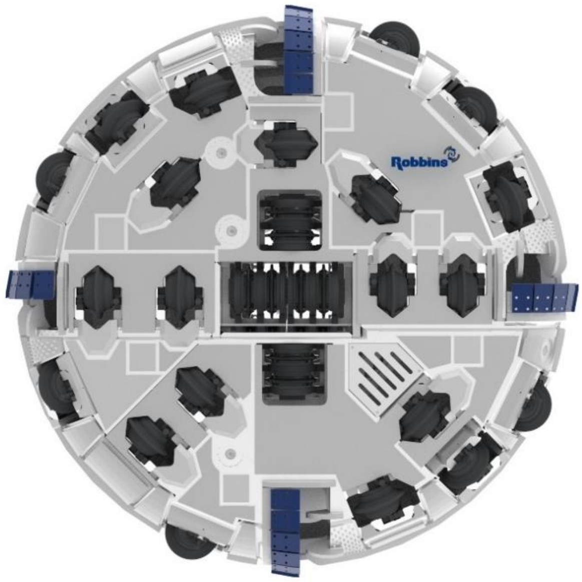

Figure 2-16 The cutterhead of Gripper TBM (Robbins)

2.4.2 Disc tools and their placement

Since the cutterhead advancement is directly linked to the cutting tools installed, the selection and placement of these tools on the cutterhead should be made carefully by experienced engineers (Figure 2-17). The first cutting tools manufactured were 10" in size and later increased to 12". However, with the introduction of the TBMs in the hard rock ground conditions, the demand grew to the new cutting tools with a larger diameter and high strength. Therefore, new 17" and 19" cutting tools with the required features were produced. In the current industry, due to its applicability in various ground conditions 17" disc cutter is mostly used. Disk cutters with a larger diameter can be used for tunnel projects in which the ground has hard rocks that are extremely abrasive (Rostami J., 2017).

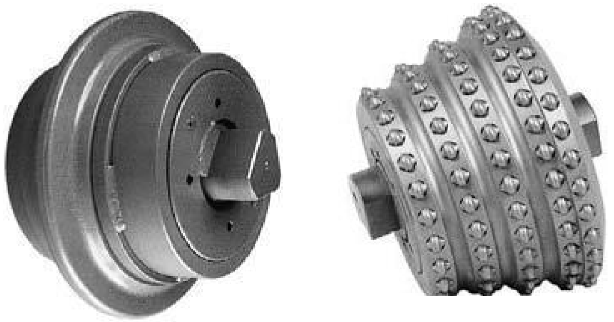

Figure 2-17 The mostly used cutting tools in the current tunnel industry

The arrangement of the selected cutting tools in terms of location and spacing is one of the main parameters that affect excavation performance (Rostami, 1998) (Roby J, 2009). Careful determination of the distance between the cutting tools is the way that allows excavations to be carried out with optimum power. As the spacing rises, the normal force applied increases as well, which means overloading the cutting tools. Thus, incorrect spacing design can, therefore, lead to cutting tool wear, which results in an increase in the operation cost. Besides, the determination of a smaller distance than the required increases the number of cutting tools to be used, which is another factor that will affect the operating costs.

Due to the wear of disc cutter caused by overload, they must be replaced after a certain time. However, the replacement is complicated enough because of the hazardous condition at the tunnel face and difficult accessibility. Several disc cutter systems are used in the current tunnel industry, which allow a disc change under the protection of the cutterhead. The two types, the wedge-lock system, and the double wedge system, are the leader in the recent market.

2.4.2.1 Wedge Lock and Double-Wedge Lock systems

The wedge lock system has two C-pieces, which are in the disc housing and are secured with a screw connection (Figure 2-18). During the installation, the disc is placed in the house and fixed by means of the fastening set, which is another essential part of the house. This set usually consists of a clamping wedge, clamping block, and fastening screw.

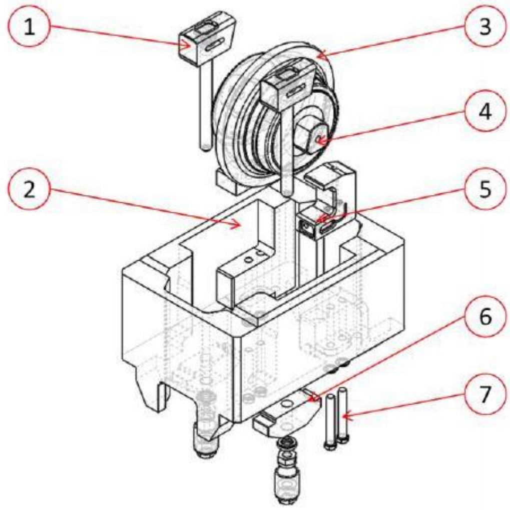

Figure 2-18 Wedge-Lock system 1) Clamping wedge with fastening screw, 2) Disc housing, 3) Cutting ring with roller base, 4) Disc Axis, 5) C-piece, 6) Clamping block, 7) Fastening

Since the double wedge is placed in the middle area, it has a narrower design compared to the wedge lock system (Figure 2-19). In the system, the fixing wedge is screwed to the disk axis to fix the disk to parallel parts and keep it stable against slipping.

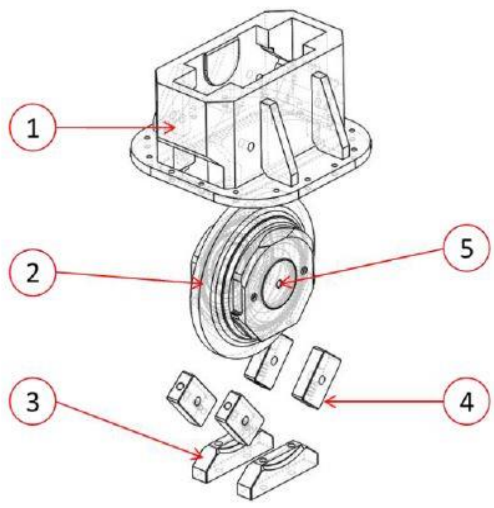

Figure 2-19 Double-Wedge system 1) Disc Housing, 2) Cutting ring with roller base, 3) Fixing wedge, 4) Parallel piece, 5) Axle flange

2.4.3 Power Units

The rotation and penetration of the cutterhead are provided by power units such as motors, thrust cylinders, and grippers. Most of the energy is whittle away by motors, which serve to rotate the cutterhead. These motors differ according to TMB types and ground conditions. Commonly used are the water-cooled electrical motors with two speeds revolution, the electrical system that allows the speed to be regulated over a wide range, and Electro-hydraulic motors. The electric motors are efficient in the ground where the hard rock exists or where the low torque is required. Generally, in terms of output and operation, these motors overcome the hydraulic system.

In addition to the motors used, thrust assemblies are also of great importance. Depending on the selected TBM, there are two ways to realize the advancement. The first one is the co-operation of the gripper shoes (Figure 2-20) and thrust cylinders. During the advancement, the grippers are tightened to the wall to keep the machine in the stable condition, and then, based on this stability thrust cylinders push the cutterhead forward the tunnel face to excavate. This process is repeated periodically after each completed excavation phase (B, 2008).

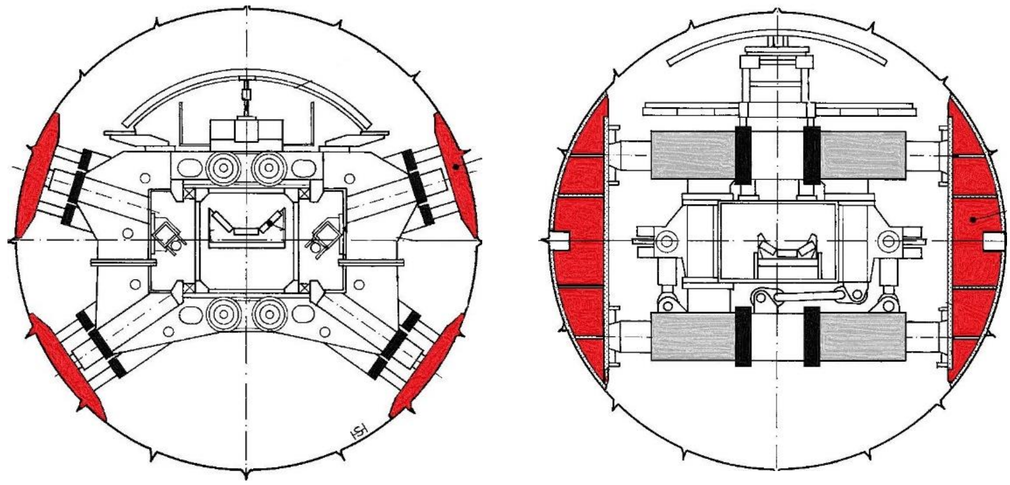

Figure 2-20 X-type gripper (Left) and Side gripper (Right) (B, 2008)

The second technique applies to the shielded TBMs in which the segments are installed. In this case, the thrust cylinders push the segment that was last installed and thus provide the advancement. The advantage of this way over the first one is the continuous tunneling provided as a result of the segment lining and thrusting can be performed simultaneously (Chapman D. N., 2017).

The gripper units not only provide pressure for the thrust but also serve to steer the TBM. This function is achieved by the interaction of hydraulic cylinders, which apply a different degree of pressure. As a result, the mean beam of TBM can move both vertically and horizontally.

2.4.4 The Gantry Part

The length of the gantry ranges from 70 to 150 meters. However, this length maybe longer, depending on the project. The parts that form the gantry differ for each TBM; but the main components are the electrical distribution systems, injection pump, support devices, cooling and filtering equipment, gas detectors, special devices that reduce the amount of dust caused by material handling, and control cabin for analyzing sensor values and controlling TBM parameters (Huang, 2008), (Chapman.P.J, 1992).

Chapter 3

3 Real-Time TBM Monitoring

In projects using TBM, some parameters need to be monitored regularly, as they influence TBM's performance and the time and cost of construction. These parameters include changes in geology, state of cutting tools and related operational factors, backfill grout monitoring, muck monitoring, pressure level monitoring in the chamber. The best way to actualize these objectives is to utilize real-time monitoring systems, which is one of the most significant contributions of modern technology to the full-face mechanized tunneling (Mooney M. A., 2012).

3.1 Changes in Geology

3.1.1 Passive Monitoring

Hard rock conditions are the main employment area of the Passive Monitoring system. The highlight of this technique is that it can be implemented in parallel with the TBM operation. The principal components of the system are accelerometers placed close to the cutterhead and providing the pilot signal, and geophones mounted on the tunnel walls to receive both direct waves and reflected waves (Mooney M. A., 2012). The signals acquired are then filtered from the direct waves using different technologies such as cross-correlation, deconvolution, frequency-wave number filtering, and become used to produce an image for ahead of tunnel face that will reveal geological state (Brückl, 2008) (Petronio, 2007). In Figure 3-1, the working principle of the technique has been illustrated.

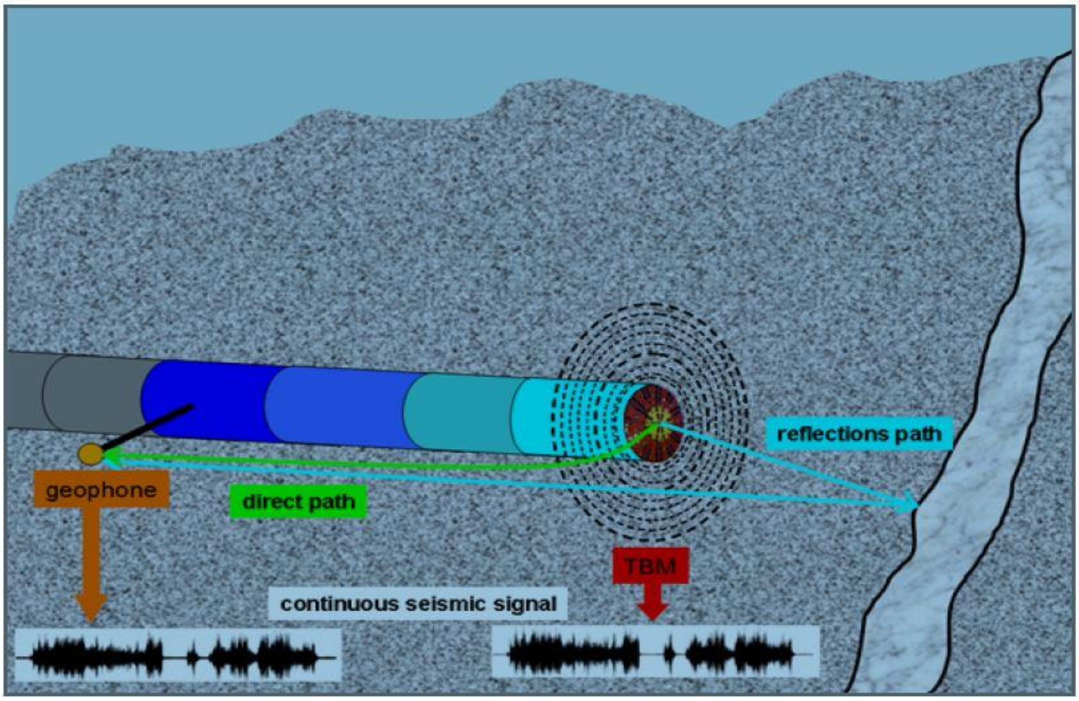

Figure 3-1 Schematic of passive monitoring involving direct transmission and reflections recorded by geophone(s) mounted behind the tunnel face and accelerometers mounted at the TBM cutterhead (Mooney M. A., 2012)

3.1.2 Integrated Seismic Prediction

Another system used in hard rock conditions is the ISP (Integrated Seismic Penetration) manufactured by Herrenknecht AG (Figure 3-2). The large-scale integration of the system into the TBM operation and its capacity to serve parallel with tunnel excavation has made it one of the most applied systems. The impact hammer that provides waves by means of blows to the tunnel wall, the geophones placed on the tunnel wall and serve to receive waves reflected by geological changes, and Data Logger are the main components that make up the ISP. The impact hammer usually generates seismic waves that turn into space waves on the tunnel face after each stroke. If the waves encounter an uncertain geological formation, reflections occur due to the density difference of the rocks, and reflected waves move back through the tunnel wall. All data gathered as a result of the system's operation is collected in the Data Logger, which also transfer data to the computer system to have the 2D and 3D image of the ground.

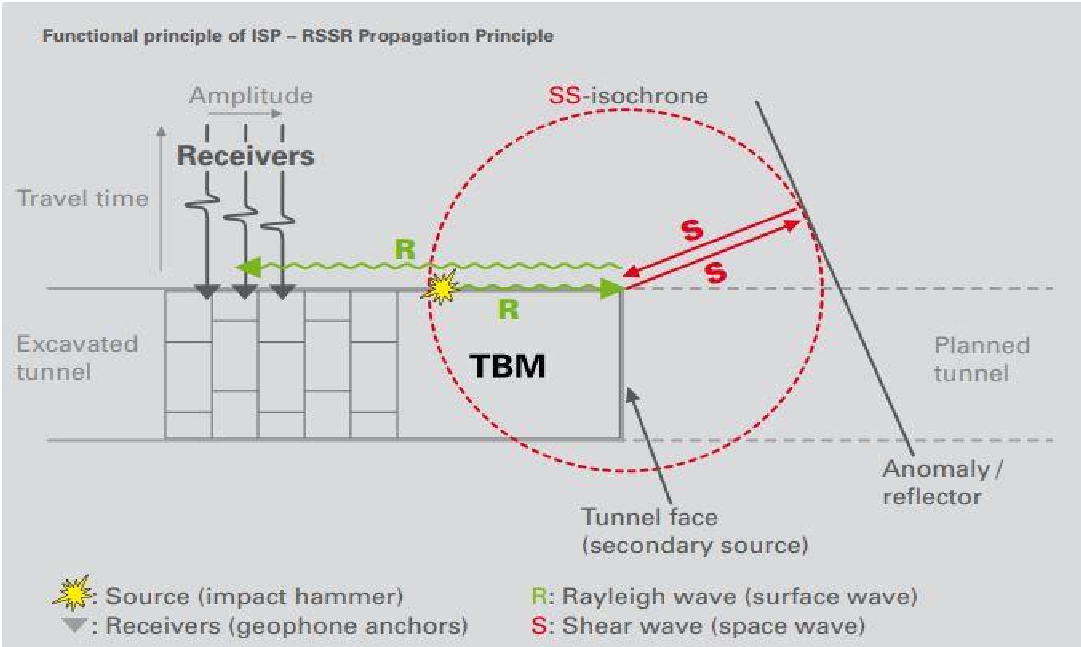

Figure 3-2 Working Principles of ISP system

3.1.3 Sonic Softground Probing

In addition to the ISP system, Herrenknecht AG has developed an SSP (sonic soft ground probing) system for use in soft, especially unconsolidated grounds (Figure 3-3). The system is generally utilized for the slurry and mix-shield machine, since soil conditioning, one of the critical factors of the EPB machine, influences the propagation of the waves to the ground. The distinctive feature of the technique is the integration of a single P-wave transmitter and multiple P-wave receivers to the cutting wheel directly. The application range is about 40 m, but the monitoring for maximum distances is not effective as it affects the resolution of the image.

During the TBM advance, acoustic P-waves are sent to the ground, and when any variations are detected in terms of density, the waves are reflected as in other techniques and collected by the receivers.

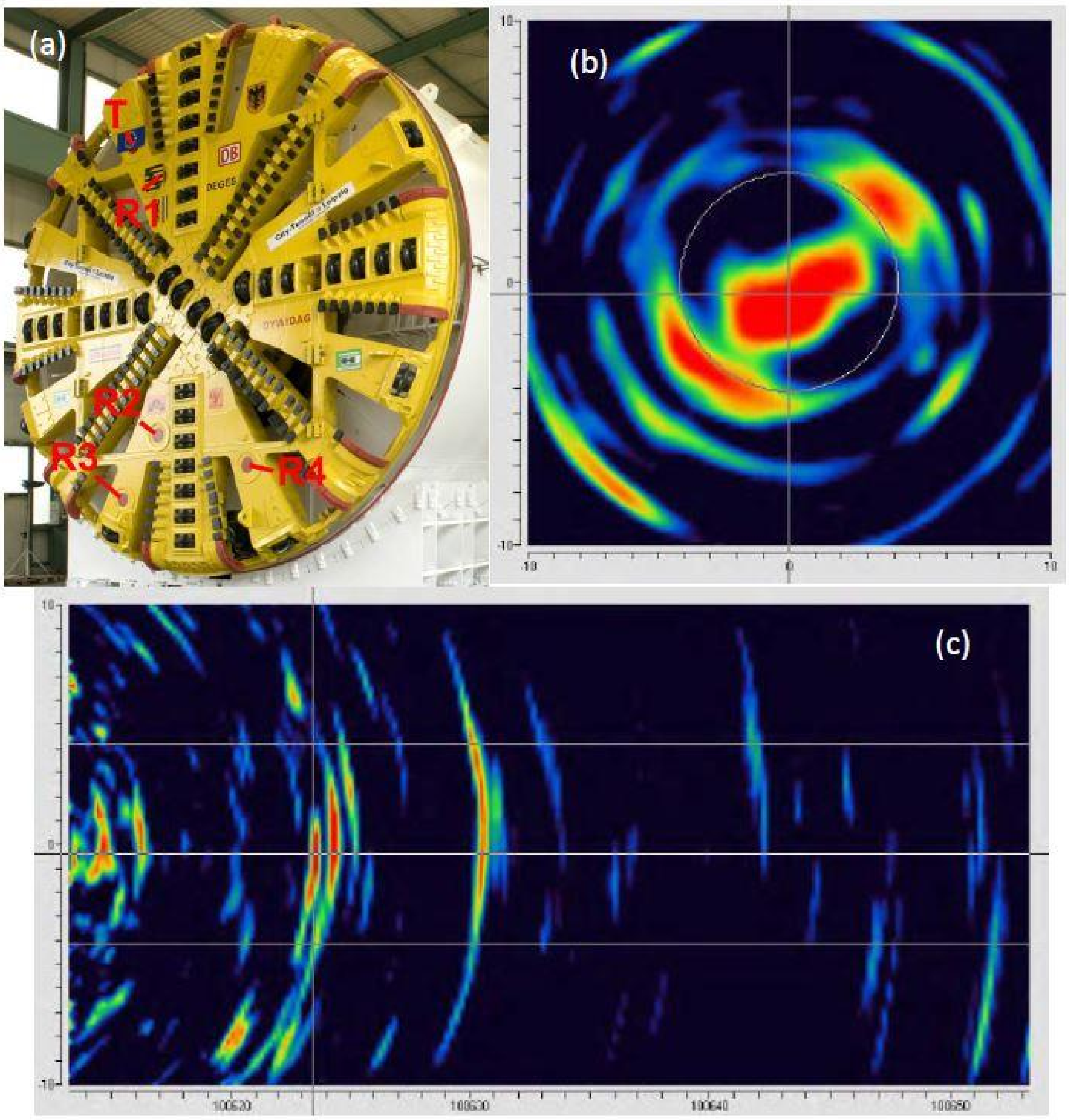

Figure 3-3 SSP example: (a) Single Transmitter (T) and 4 receivers (R1-R4) integrated into the 9.0 m diameter cutterhead used for the Leipzig city tunnel project; (b) acoustic reflection from a sealing block 10 m ahead of the TBM; (c) plan view reflection of sealing block ahead of TBM (Mooney M. A., 2012)

3.2 Backfill Grout Monitoring

The most common challenge for tunnel projects held in urban areas is the subsidence of the surface due to the low self-bearing capacity of the soil. Therefore, in order to minimize subsidence, the excavation face needs to be supported regularly. In this sense, EPB and Slurry machines are very efficient (Guglielmetti.V, 2008).

In addition to the face support, the filling of the void between segment and ground is another important factor that reduces the subsidence. The outer diameter of the segment is usually smaller than the shield; therefore, after installing each ring, a gap is created which must be filled between the segment and the ground (Peila D., 2011) (Figure 3-4).

Due to the following reasons filling of this void is critical:

- Reduction / Elimination of subsidence
- Protection of tunnel against the water inflow
- Locking the segment to the position
- Reduction of the load, which each segment is exposed.

Recently three types of injection techniques are used for backfilling. The first and traditional one is the injection of the mixture through holes present on the segment lining. The second way is the longitudinal injection from the shield. Finally, longitudinal injection through shield by using two component grouting systems. Another important parameter is the proper mixture selection. The possible mixtures are cement-water, cement mortar, cement-bentonite, inter mortar, pea-gravel and cement, and clay (Russian) (Peila D., 2011).

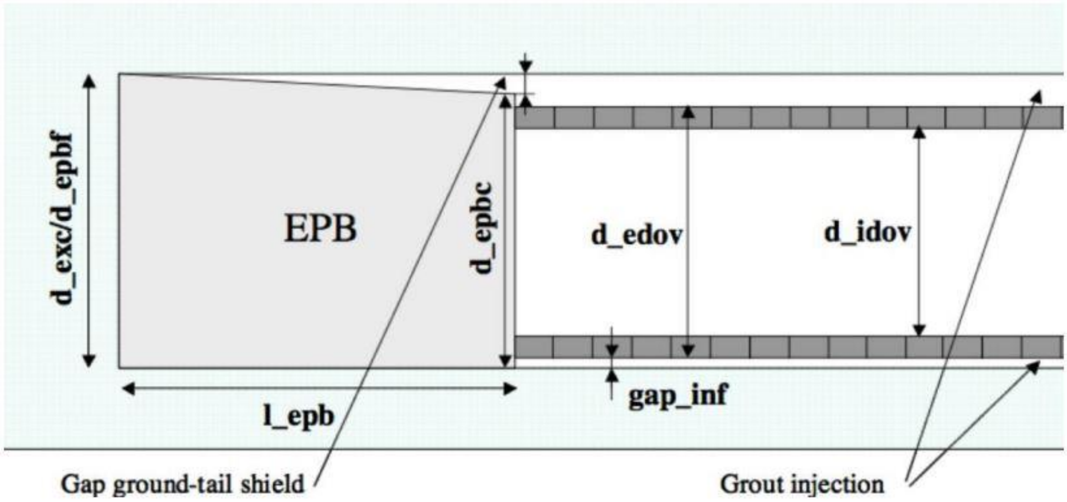

Figure 3-4 Schematic representation of annular gap and grout injection (Shah, 2016)

Despite backfilling is typical for soft ground tunneling, it can also be applied in Single Shield TBM operation in case of high-water inflow. However, the injection technique will be different from the soft ground since backfilling starts from the bottom part in hard rock.

The filling process includes several parameters to be monitored: mortar volume control, filling pressure, and mortar properties to be monitored. However, during TBM boring, grout volume and injection pressure are of great importance due to their criticalities. Due to the stated reasons, by recording the number of strokes during the injection by TBM data acquisition system, grout volume of backfilling is monitored. According to (Mooney M. A., 2012), the sophisticated technique would be to place small size and cheap sensor in the grout to ensure accurate grout volume monitoring.

Another critical factor in backfilling is the injection pressure, which is usually measured in the grout pipe in the shield or in the concrete segment. TBM's advance speed and grout injection are interconnected works. In particular, the advance speed must be adjusted by considering the backfilling process in order to fulfill the pressure index prescribed during the design phase. The proper monitoring of the injection pressure reduces the incomplete backfilling risks during the over-excavation and losses of the grout.

3.3 Pressure Level Monitoring

As stated before, tunnel projects that take place in soft ground conditions require regular support of the excavation phase due to the tendency of ground to move. In this sense, EPB, which utilizes the excavated material to support the face, is one of the most involved machines. Taking into account the terrible consequences of surface settlements, the level of pressure in the excavation chamber, which regulates the applied pressure, is monitored regularly during TBM advance. The main parameters that influence this level are the speed of screw conveyor and conditioning agents that change the muck properties for being used with support purposes. The recent EPB TBMs have been equipped with a pressure cell, which monitors the pressure level inside the chamber and transmits the corresponding data to the driver cabin in real-time. Thanks to this operation, the TBM driver is able to adjust the pressure level and quantity of conditioning agents. Most of the recent monitoring systems utilize the average value of the pressure recorded by individual sensors at different cutting wheel levels (Herrenknecht AG). A detailed information regarding pressure sensors and their application can be found in (Bezuijen, 2005), (Mosavat.K, 2015).

3.4 Cutterhead Monitoring

Cutterhead monitoring mainly includes the monitoring of cutter tools, their temperature, wear level, applied cutting force per disc, the vibration of cutterhead (Samuel, 1984) (Moulin, 2010) (Shanahan, 2011). In this context several cutter monitoring systems have been introduced, for instance, DCLM, DCRM by Herrenknecht AG, eddy current displacement sensor by (Lan, 2019), parallel laser light path technique (Bing, 2013) and new disc cutter tools that can detect the wear thanks to the hydraulic pressure alterations (Mao, 2012).

Disc Cutter Rotation Monitoring system that developed by Herrenknecht AG is one of the applicable techniques in order to determine the rotation, temperature thus the wear of cutting tools. The hard rock conditions are the main application area of the system while they are usually used with 17- and 19-inches disc tools.

The system's unique features are its low installation time, low space requirement, and its ability to be installed not only on the new TBM but also on the machines that are running. The sensors have been designed to record the signals that occur after each rotation of the cutting tools and transfer them to the TBM's driver cabin in real-time. In addition, the sensors have the function of measuring the temperature around the disc cutters, so that high temperature is one of the main determinants of the wear of the cutters.

The second monitoring system from Herrenknecht AG is the Disc Cutter Load Monitoring system, where the main target is to determine the applied cutting force, transmit the corresponding data to the driver cabin in real-time, avoiding the excessive load, thus reduction of the downtimes. Thanks to the special monitor placed in the cabin, the driver is able to regulate the applied cutting force accurately and also to see the real position of the boulder, which is not present in the existing in the preliminary geological profile. Early detection of these formations and force measurement allow reducing the cutter wear and the cost of the operation. However, it also should be noted that the monitoring of the cutting force by means of the DCLM sensor also depends on the TBM driver's professionality. An additional benefit of the system is that it is capable of providing data that can be used to develop the geological map of the excavation face.

The most recent real-monitoring system is an eddy current sensor, which determines the cutter wear thanks to the distance between the cutter edge and the sensor, before and after cutter wear. Figure 3-5 illustrates the monitoring scheme of the sensors.

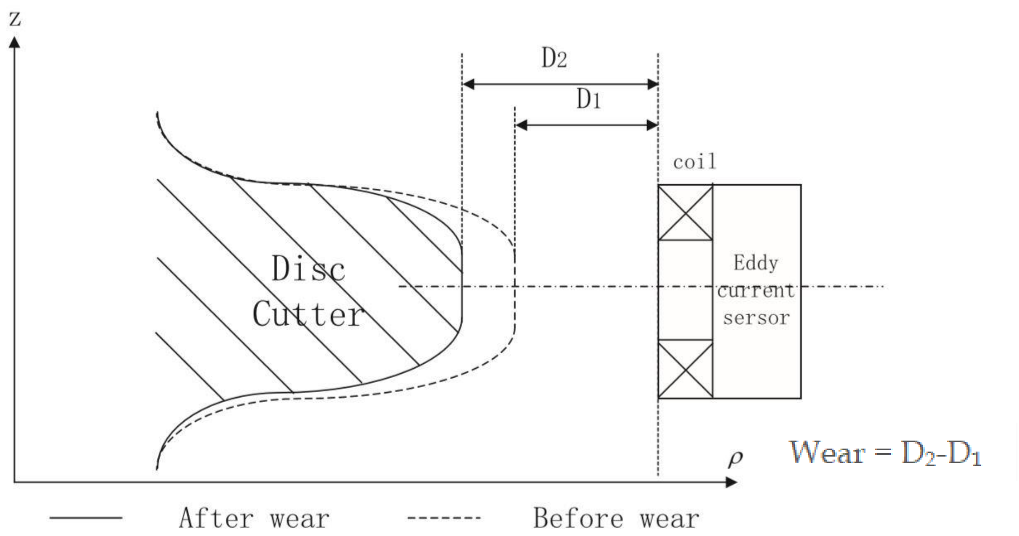

Figure 3-5 Measurement schematic diagram of disc cutter wear amount(Lan, 2019)

3.5 Muck Monitoring

Another important parameter in mechanized tunnel projects is muck transportation. Especially during the application of EPB, the correct adjustment of muck transportation become critical due to its influence on pressure control, surface subsidence, and so on. In this context, different technologies can be applied; however, the most productive is the belt scale and/ or a laser scanner (Figure 3-6).

The fundamental of the belt scale is to measure the weight of the muck by means of the set of the roller, while the laser scanner measures the profile of the material. The in-situ soil density, water inflow, and muck density are the unknown parameters, which cause some difficulties in the laser scanner application.

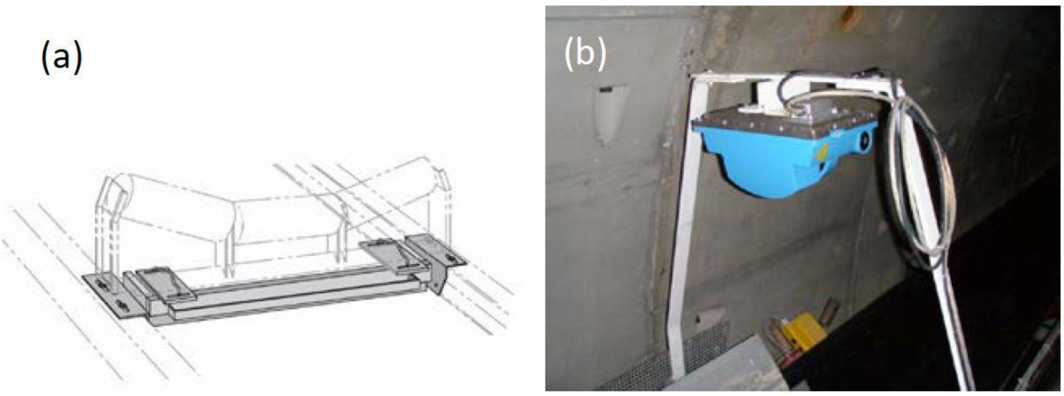

Figure 3-6 (a) Belt weigh, (b) laser scanner (Mooney M. A., 2012)

In addition to EPB muck monitoring, (Whermeyer, 2000) had developed a system that made it possible to monitor muck in the Slurry TBM. The system's essential tools were the density meter and flow meter mounted on both the feed and discharge portions of the slurry line. He also underlined that this monitoring technique is applicable only to horizontal and long slurry pipes, not vertical - due to the limited space.

Chapter 4

4 Disc Cutter Load Monitoring

In the recent mechanized tunneling industry, the first target of TBM manufacturers is to increase automation of the machine operation, thus decreasing the related costs and construction time. One of the important sources of expenditure in the mechanized tunneling is the tools that need to be replaced due to the damage. For instance, due to wear factors cutting tools are replaced after covering a certain distance. The main reasons for this wear are the existing geology, applied cutting force, and sometimes the stuck of tools. Among these factors, the applied cutting force could be considered as the most critical due to its influence not only on cutting tools but the general machine, advance rate. Therefore, it is essential to set the cutting force properly since it reduces spending and increases the advance rate of TBM.

Numerous researches have been done in the past concerning cutting force measurement. The first was made by (Gobetz, 1973) who successfully analyzed a 12 ft of the introduced tunnel project and revealed that cutting force change regularly as the machine advances. Also, peaks of applied force were higher than expected. (Hopkins M. J., 1979) performed the analysis in order to measure the force of raise boring machine by using strain gauges. However, despite the fact that data transmission was carried out faster thanks to the telemetry system, this approach was still not durable. (Samuel, 1984) developed a method that was able to perform analysis in a large context. The research was carried out in the laboratory by utilizing a small-scale cutting machine. They installed two strain gauges in cutter and continued analysis for 20 minutes. The results of this technique were in contrast with previous models due to the observed frequency (10 Hz). This technique was faster and cheaper than previous ones; however, due to the challenges of ground in real tunneling activities, the system was not feasible to use.

4.1 The First Stage of DCLM Development

The DCLM system was introduced during 2013 – 2015 throughout EU-funded DRAGON project. The fundamental of the Disc Cutter Load Monitoring was to monitor the corresponding load per disc and transfer the relevant data in real-time. The system has its own monitor placed in the TBM driver's cabin, and thanks to this monitor, the driver can regulate the applied force and see the boulder position where the load needs to be increased.

4.1.1 Measurement Technology and Implementation

4.1.1.1 Strain Gauge Measuring technologies

A Strain gauge is a proven technology in identifying near-surface stress, thus the stresses on the main component (Figure 4-1). The fundamental of this technology is the conversion of force, weight, tension into the electrical resistivity changes that can be estimated later. The term named strain is considered to be the proportion of variation in the length to the original unstressed length of the component. This technology has been implicated in numerous researches regarding cutting force measurement, for instance, (Zhang Z. X., 2003), (Gobetz, 1973).

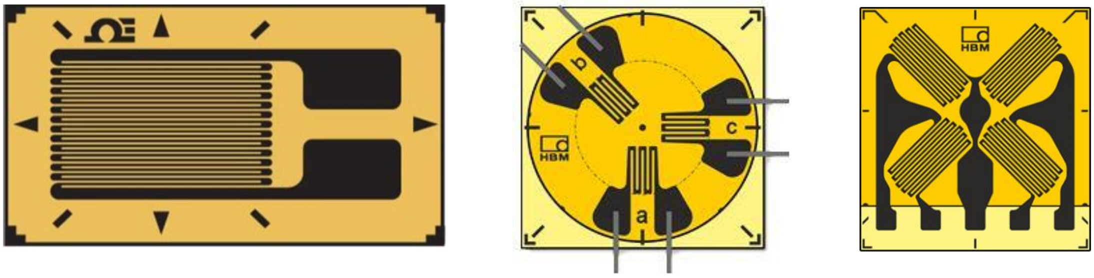

Figure 4-1 The possible strain gauges technologies used in TBM tunneling

4.1.1.2 Selection of the measuring points

During the development of the DCLM system, determining the location where the sensors will be installed was one of the most important points, as it affects the sensor design and the overall efficiency of the system. In this context, the cutter box includes disc axle, the insert, and clamping devices was simulated by FEM (Figure 4-2). According to the FEM analysis, the highly stressed areas where the sensor could be positioned were clamping devices, disc axle, and the axle's direct bedding area. However, in the further development of the system, it was identified that disc cutter axle and clamping devices could not be an option for sensor location since they will disturb the cutter change activities. Thus, bedding area of the axle was selected to fit the sensor [12]

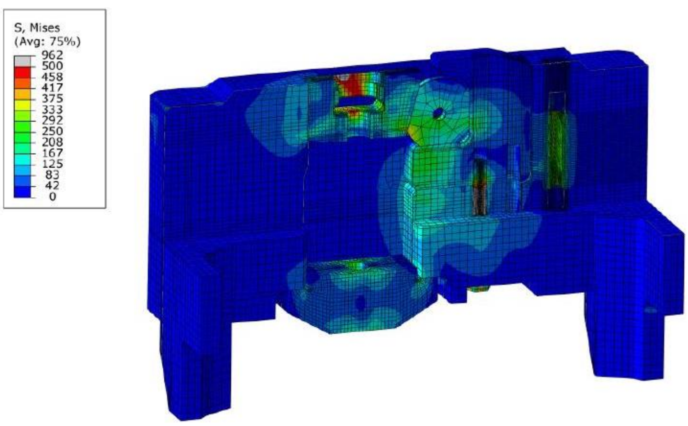

Figure 4-2 Cut view of the simulation of the wedge-lock system (Barwart, 2015)

In terms of the integration of the sensor into the fastening set of cutters, three possibilities were introduced (Figure 4-3). The first one, which placed between cutter housing and the insert, was developed by Herrenknecht. The piezo-electric load cell was the fundamental of this option. The second option, which was based on the pre-stress reduction of the fixing bolts, had been established by Entacher. Finally, the last option, which was considered as the best one, due to the accuracy of recorded data, and protection system against the harsh condition while cutting the tunnel face.

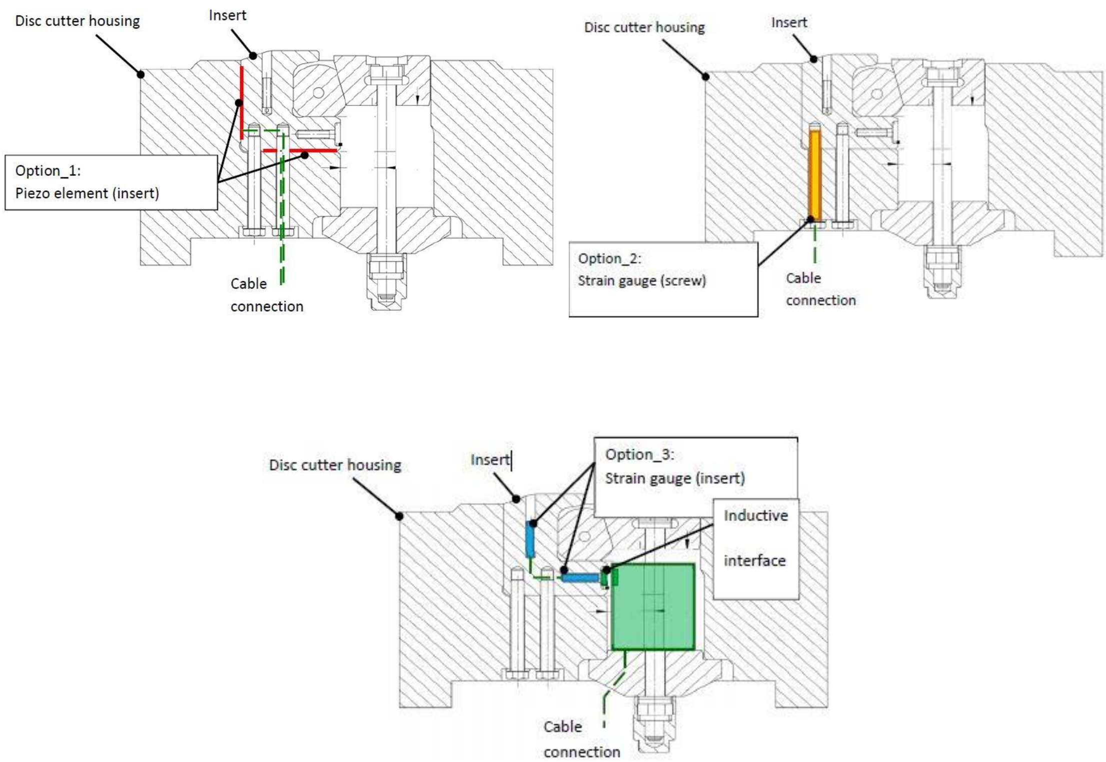

Figure 4-3 Various options for sensor placement

4.2 Application Modes

4.2.1 Open-Mode

Developed DCLM system had a different installation and benefits depend on the integrated TBM type. In this sense, open and closed mode DCLM systems were available. Open mode which is mainly mounted on Gripper (Open) TBM had been designed to work under stable conditions where the excavation chamber was empty and not pressurized (Figure 4-4). This working condition allowed to actualize the online data transmission by means of radio signaling.

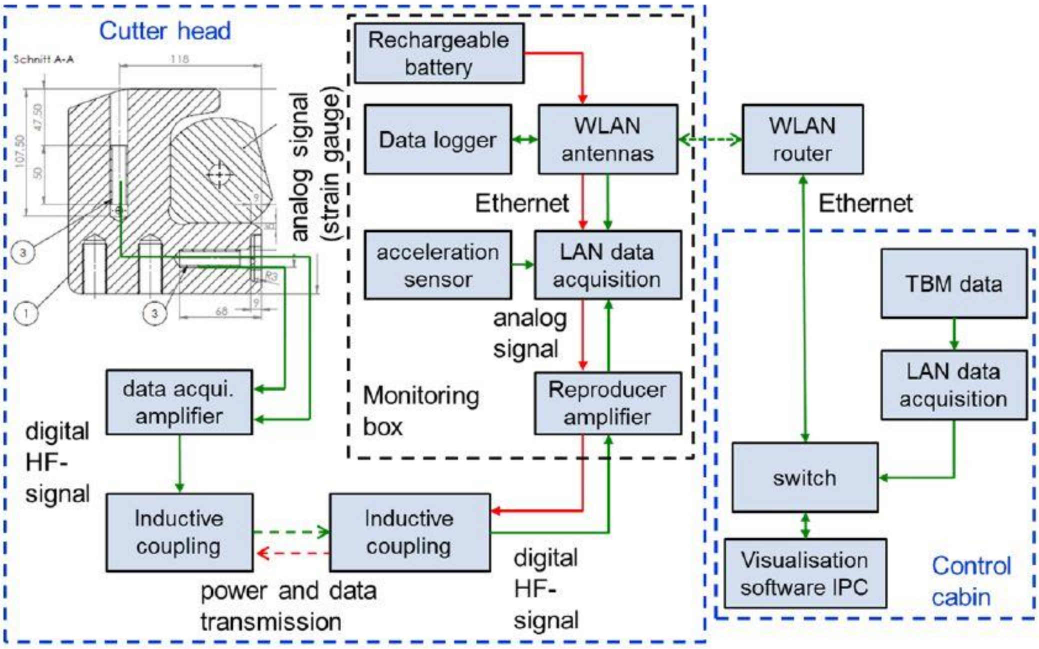

Figure 4-4 Open-Mode Telemetry system

As it can be noticed from Figure 4-4 the C-pieces of disc cutter has been equipped with strain gauge technology which has a connection to data acquisition system. Then inductive coupling has been added in order to avoid the risks in difficult tunneling conditions.

4.2.2 Closed-Mode

In contrary, closed mode mean that typically for shield machine in soft ground condition where the excavation chamber is filled and pressurized thus radio signaling replaced with online data transmission (Figure 4-5).

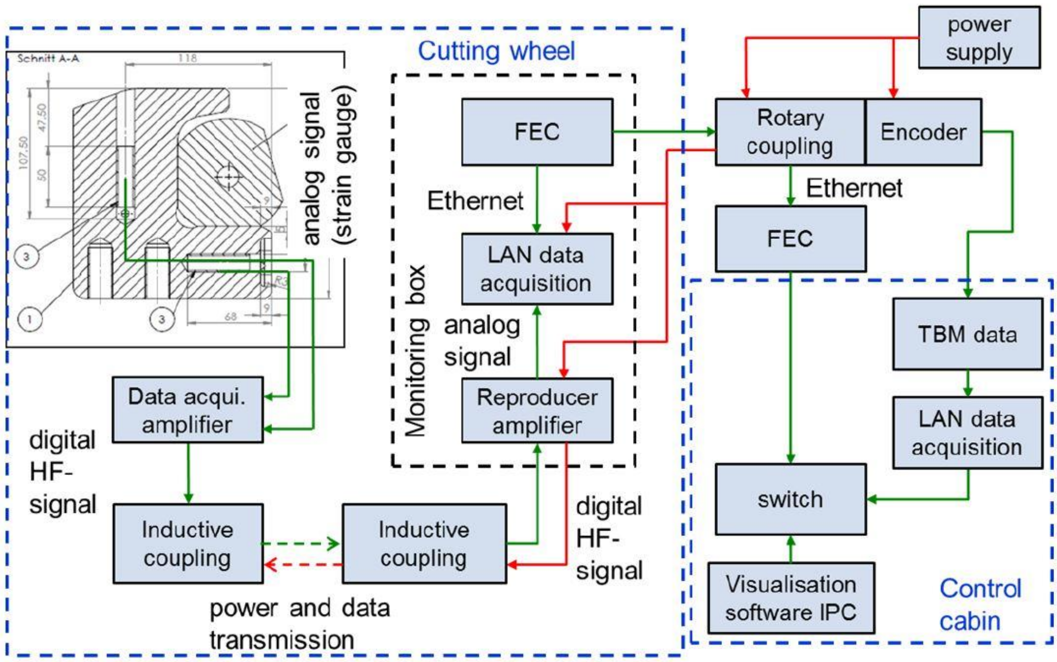

Figure 4-5 Closed-Mode Telemetry system

4.3 Current DCLM system

After implementing the first DCLM system in the job-site, several difficulties appeared. For instance, the number of electric cables, the installation difficulties also the place where the sensor had been installed was not the best location. Finally, the system was not durable for the long project since it was too sensitive to the vibration, for example, caused by the TBM advancement and cutterhead rotation. In consideration of all these drawbacks, Herrenknecht developed the DCLM system and achieved its successful application in the real tunnel projects. The most significant difference between the new and old systems was the replacement of all the electrical cables with the digital system. Also, the most appropriate location for sensor placement was identified (Figure 4-6).

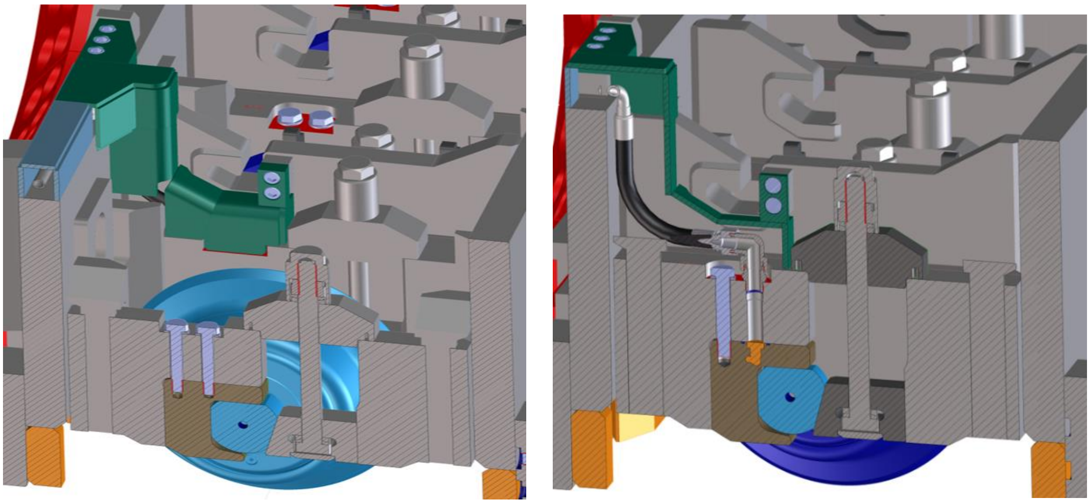

Figure 4-6 The most recent DCLM sensor placement (Herrenknecht AG)

Currently, based on the employed Tunnel Boring Machine, there are two types of DCLM systems, open (DCLM-HR) and close (DCLM-SG). DCLM-SG provides more advantages than DCLM-HR. The benefits of closed mode are:

- Online information of possible contact with boulders
- Visualisation of critical loads caused by boulders to assist the TBM driver
- Data acquisition and data management for learnings
- Support of the TBM driver to avoid significant damage of the cutting wheel and its tools
- Robust system for detecting obstacles

The open mode has only two advantages:

- Visualisation of heterogeneous formations / instable heading face

- Online monitoring and detection of Disc Cutter overloads

In Figure 4-7,Figure 2-1 , Figure 4-9 and Figure 4-10 the design of the system for the open (operating) mode - means hard Rock application - as well as for the closed (operating) mode - means soft-ground application - is schematically shown. According to that, the power supply for the open (operating) mode is carried out by an inductive coupling mounted in the cutter-head center and the data transmission by permanent radio communication Apart from that, the energy and data transmission for the closed (operating) mode is realized by completed cabling using a rotary coupling with additionally adapted slip ring assembly.

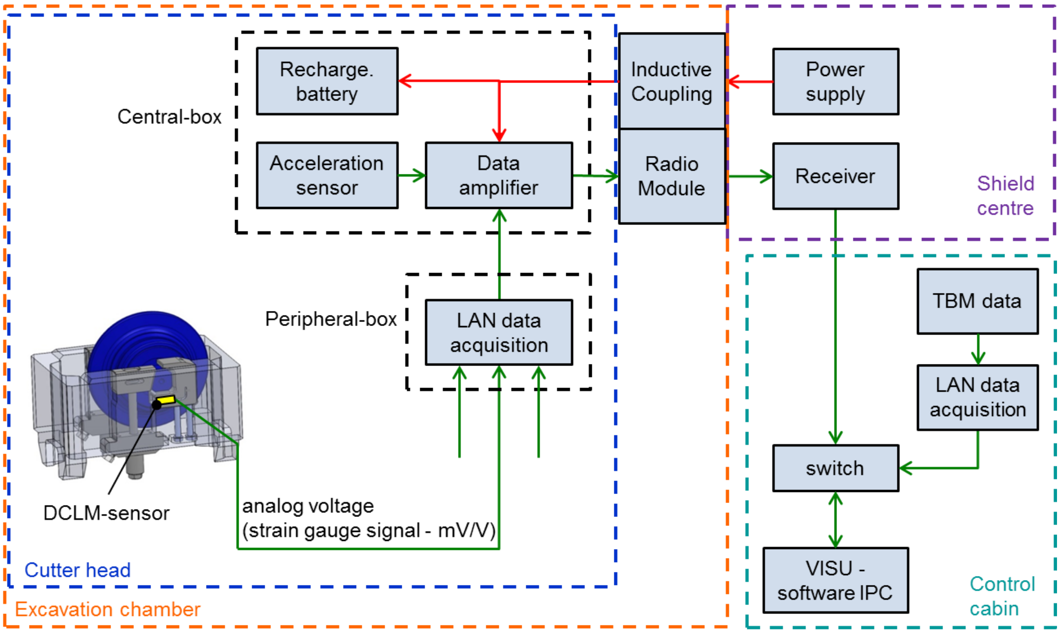

Figure 4-7 The recent Open-mode telemetry system (Herrenknecht AG)

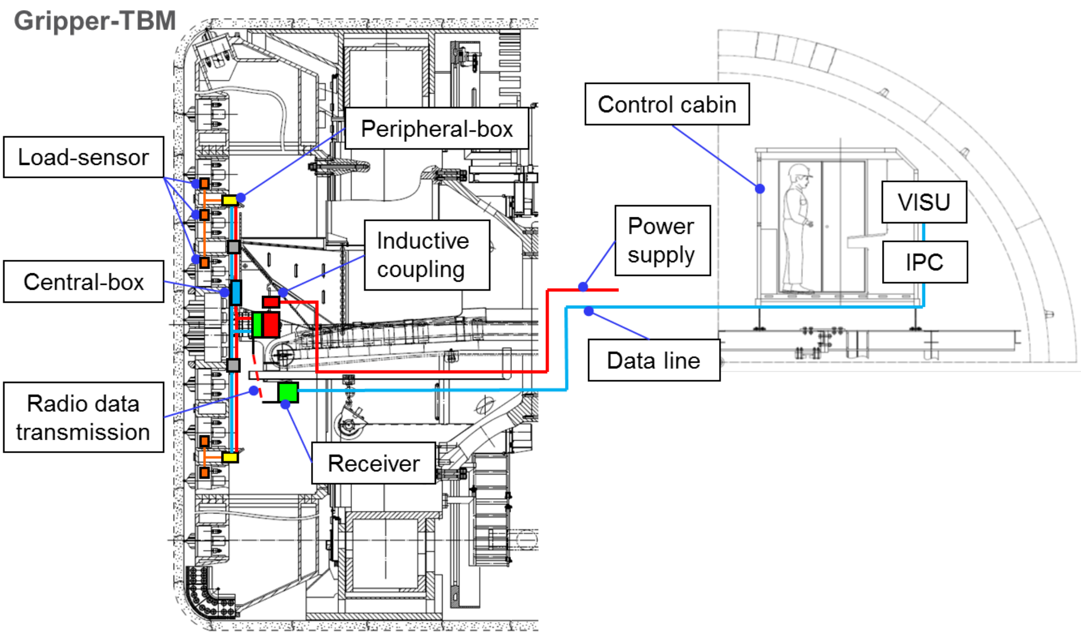

Figure 4-8 Installation of DCLM system in Open-TBM (Herrenknecht AG)

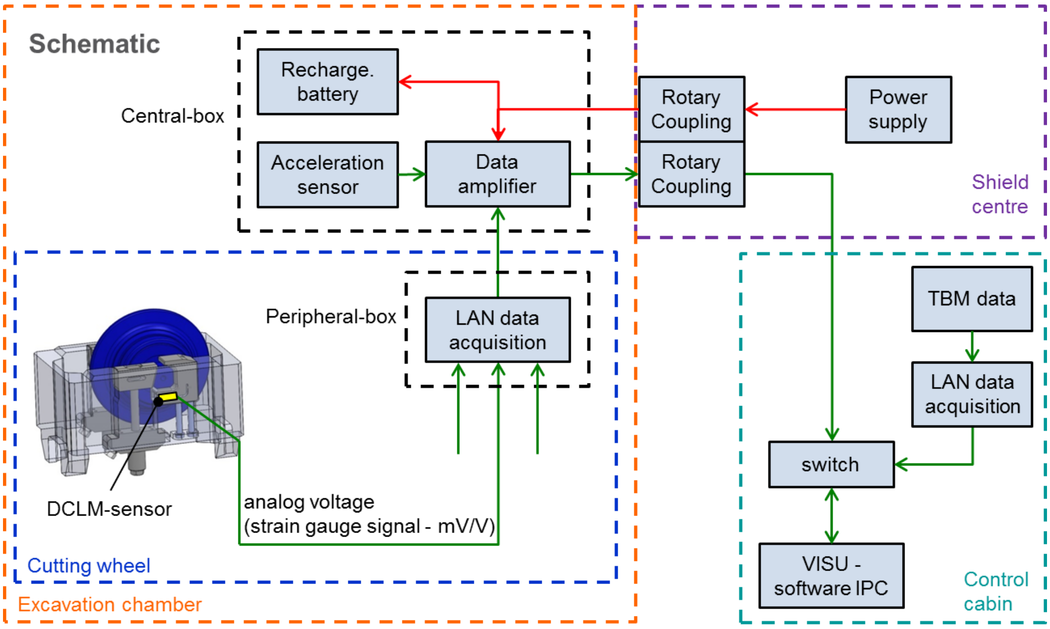

Figure 4-9 The recent Closed-mode telemetry system (Herrenknecht AG)

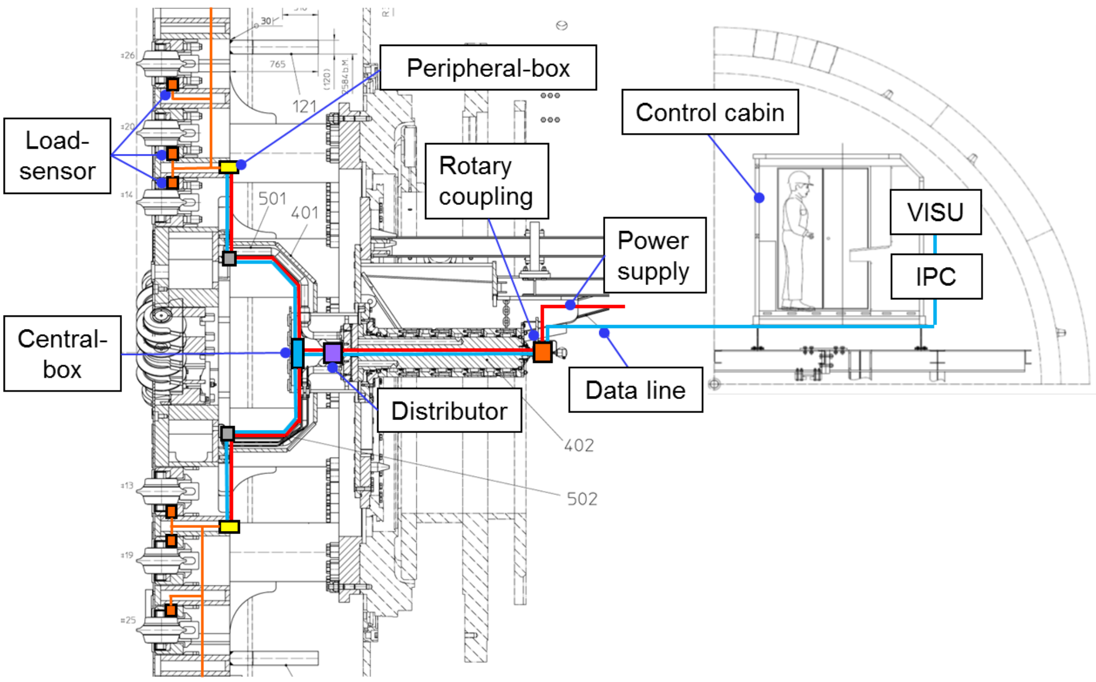

Figure 4-10 Installation of DCLM system in Close-TBM (Herrenknecht AG)

From operating point of view, the cutter insert of the fastening set is equipped with the DCLM-sensor and cable-connected to the data-acquisition. The measured data of the impact load is transmitted to the data processing and visualization in the control cabin in real-time. In combination with the determination of the cutter-head position and, therefore, also the current positioning of the particular disc cutters in real-time enables the continuous visualization of the local impact load at the heading face (Figure 4-11).

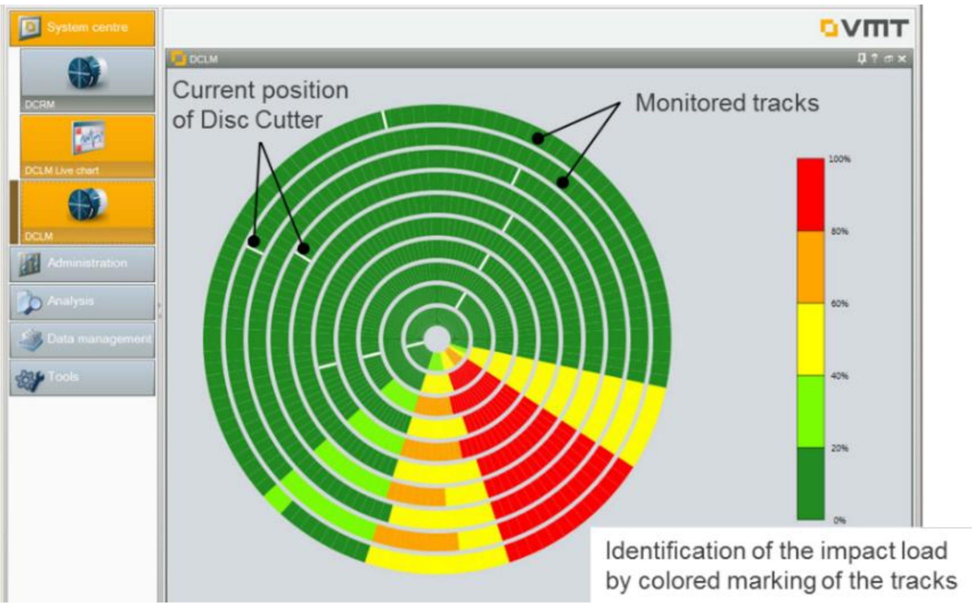

Figure 4-11 Radar Image of Disc Cutter Load Monitoring from TBM driver's cabin (Herrenknecht AG)

4.4 Face Mapping

The DCLM system has a similar concept with ShapeMatrix in terms of face mapping. So, during the advancement stop, the cutterhead is occasionally retracted for a certain distance, and the camera for the photo-optical recording of the heading-face is installed on five different positions inside of the cutter-head (Figure 4-12).

On every camera installation position, a defined overlapped photo-sequence is made each in connection with one cutterhead revolution for creating five ring-shaped images at first. Afterward, these five pre-processed Ring-shaped images are overlapped again to one overall heading-face image by the same application. Due to the limited installation positions of the camera, the center area, as well as the gauge area, cannot be recorded completely.

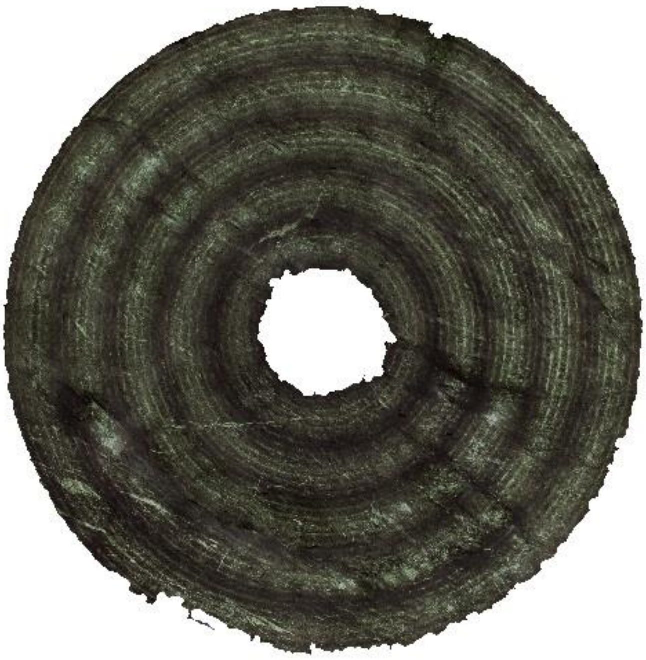

Figure 4-12 Geological model of excavation face (Herrenknecht AG)

This created heading-face image is compared to the recorded DCLM-data just before the advance stop. For that purpose, the visualized DCLM-data is overlapped to the real heading-face image in order to firstly contrast the areas of less respectively no impact load with the Break-outs at the heading-face optically. According to this, a certain correlation is clearly identified (Figure 4-13).

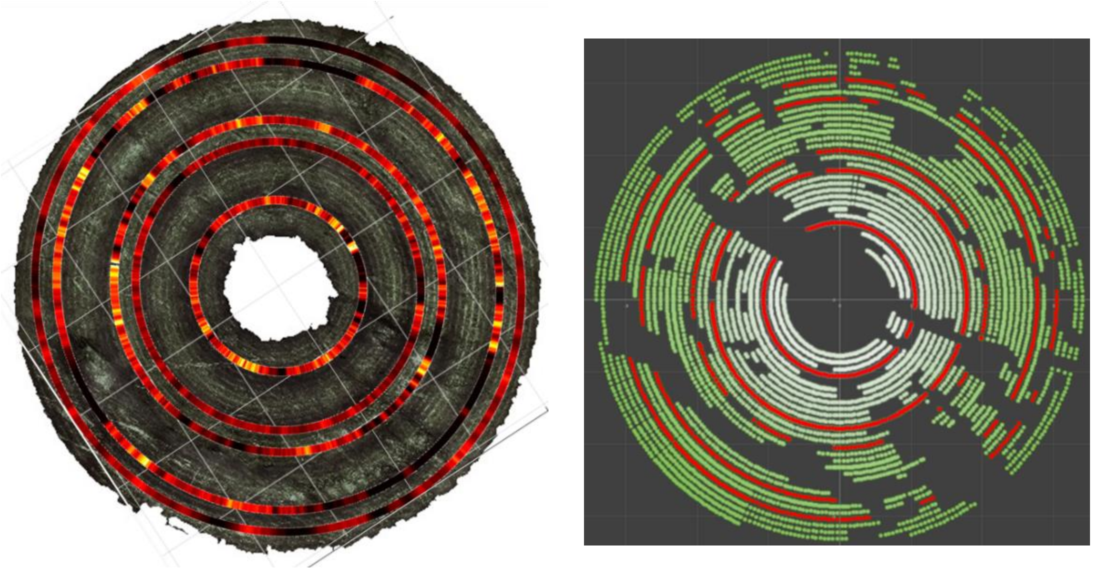

Figure 4-13 Correlation of DCLM data with Geological model (Herrenknecht AG)

In order to be able to compare the recorded DCLM-data with the real heading-face image in detail, the break-outs at the heading-face without recognition of the track are identified and transferred into a coordinate system (Figure 4-13).

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Chapter 5

5 Project Specification

By the end of the 1960s, the PWD (Public Works Department) outlined a Sewerage Master Plan to cope with the challenges of growing population and industrialization and to further improve Singapore's sewerage system. Under this plan, six sewage treatment plants, one sludge treatment plant, and 139 pumping stations would be set in the different parts of Singapore.

Despite the successful utilization of the plan until 1997, the water pollution that began in 1995 due to corroded pipes and the existing system, which took up much space, made it inevitable to create a new system. In this context, the government put forward the DTSS project (1995), consisting of two deep tunnel sewers, two water reclamation plants (WRPs), a network of link sewers, and deep-sea outfall pipes. In DTSS, thanks to the gravity, the water would be conveyed through the deep tunnel sewers to the WRPs, where the water would be treated into ultra-clean, high-grade reclaimed water called NEWater, then discharged to the sea.

DTSS project consists of 2 Phases. Phase 1, comprising of the North and Spur tunnels, the Changi water reclamation facility, and the overfall, was completed in 2008, while Phase 2 is still under development and is expected to be completed by 2025 (Figure 5-1). The main mission of the DTSS project is to join Phase 1, serving the western part, and Phase 2, working the eastern part of Singapore and creating a single system that can satisfy both the country's current and future demands.

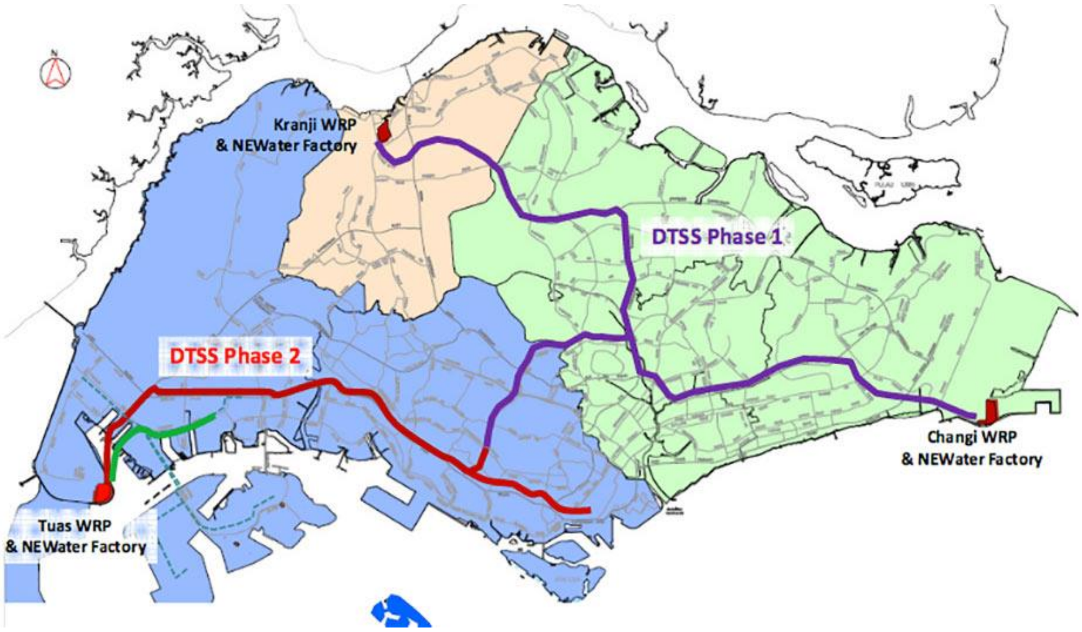


Figure 5-1 Scheme of DTSS Phase 1 and DTSS Phase 2

Phase 2, with a total length of 50 km, consists of five different design contracts (Appendix 1). In this study, the main focus will be given to Contract T-09, which is 8km long with 6 m inner diameters, as it provides data for this research.

5.1 Ground Investigation Activities

5.1.1 Geophysical Survey

Seismic Refraction (FR), Seismic Reflection (FL), and Electrical Imaging (EI) were adopted as the land geophysical survey techniques. The objective of the land geophysical survey works (FR, FL and EI survey) are to map out the underground soil and rock profile at the concerned area, and to detect the fault line or discontinuities if any.

5.1.2 Field Tests

Field tests carried out include the Standard Penetration Test (SPT), Pressuremeter Test (PMT), Field Permeability Test, Field Vane Shear Test and Televiewer logging surveys (optical or acoustic techniques).

The SPT tests were carried out to determine the relative density and consistency of the sub-soils and to obtain disturbed samples for visual soil description. The pressuremeter test (PMT) was performed to determine the deformability and strength properties for the soil. Field permeability tests were also conducted at selected boreholes. Falling head method was used to determine the in-situ permeability of fine-grained soil strata. Field Vane Shear Tests were performed to determine the undrained shear strength of soft cohesive soils while, Televiewer logging survey (optical or acoustic) was performed at selected boreholes to obtain qualitative imaging of the rock surface surrounding the borehole wall. It provides information for fracture detection, detection of thin bedding, determination of bedding dip and orientation, frequency and aperture size of the fracture.

5.1.3 Laboratory Tests

The laboratory tests carried out on soil samples includes the following:

a) Index/Classification Test

    (i) Bulk density

    (ii) Dry density

    (iii)Specific gravity

    (iv)Moisture content

    (v) Atterberg limits (liquid and plastic limits)

(vi) Particle size distribution test using wet sieving and hydrometer testing methods (with dispersant)

b) Strength Test

(i) Unconsolidated undrained (UU) triaxial compression test

(ii) Consolidated Isotropic undrained (CIU) triaxial compression test with pore water pressure measurement (single stage/multistage)

c) Consolidation Test

(i) 1-D Oedometer test

d) Chemical Test

(i) PH value

(ii) Total sulphate content

(iii) Chloride content

(iv) Organic content

The laboratory tests carried out on rock samples includes the following:

a) Index Test

(i) Density test

b) Strength Test

(i) Unconfined compression test

(ii) Point load test

c) Abrasion Test

(i) CERCHAR test

5.2 Regional and Tunnel Route Geology

According to the ground investigation, at the location of the shafts and along the tunnel alignment, the geology is mainly composed of residual soils and weathered rocks of Jurong formation covered by superficial Fill deposits, and various soils of Kallang formation.

The Jurong formation, which was laid down during the late Triassic to early Jurassic periods, consists of a wide variety of sedimentary rocks. Formation underlies most of the western and south-western areas of Singapore. The weathering grades of the Jurong Formation are described in Table 5-1.

Grade	Basis for Assessment
I	Intact strength unaffected by weathering
II	Slightly weakened, slight discoloration, particularly along joints.
III	Considerably weakened & discolored, but larger pieces cannot be broken by hand. Rock Quality Designation (RQD) is generally > 0, but RQD should not be used as the major criterion for assessment.
IV	Core can be broken by hand or consists of gravel size pieces. Generally, highly to very highly fractured but majority of sample consists of lithorelicts. (RQD generally = 0, but RQD should not be used as the major guide for assessment). For siltstone, shale, sandstone, quartzite and conglomerate, the slake test can be used to differentiate between Grade (slakes) and Grade (do not slake).
V	Rock weathered down to soil-like material but bedding intact. Material slakes in water.
VI	Bedding destroyed.

Table 5-1 Weathering Grades of Jurong Formation.

Kallang formation covers a substantial portion of the land area of Singapore. These deposits are marine, alluvial, littoral, and estuarine in origin and were laid down during the Holocene and late Pleistocene age. The formation can be found near coastal areas and river valleys. It commonly overlies the eroded residual upper surface of the Jurong formation.

The main member of the Kallang Formation is the Marine Clay (M), which is very soft, silty, kaolin-rich clay with disseminated shell fragments.

The other members of the Kallang Formation are the Estuarine Clay (E), Fluvial Sand (F1), and Fluvial Clay (F2). The Estuarine Clay is soft, high in organic content, and often exists in localized patches directly below the fill or marine clay. The Fluvial Sand comprises of clayey or silty sand with SPT up to 18 blows/ 30 cm, while the Fluvial Clay exists as a soft to firm sandy clay, clay, or sandy silt with SPT up to 8 blows/ 30cm. The Fluvial sand, clay, and Estuarine exist in localized patches of varying thickness at shallow depth and are usually interbedded.

Fill is a man-made heterogeneous deposit comprising of sandy/ clayey materials intermixed with gravel, tar, and rock fragments. These materials are likely to be variable in-depth and composition. The fill layer encountered in the land boreholes is relatively thin, with thickness typically between 2 to 8 m. It usually exists as a layer just below the ground surface.

Based on the drilling data, it was defined that the geology where the tunnel passes through is predominantly composed of sedimentary soils and rocks of the Jurong formation Drilling activities revealed that there is a possible limestone zone in the geological profile between Shaft N1 and N2, Shaft O1 and O2, Shaft O2 and O3, Shaft N3 and N.

Some of the limestone layers are found in the upper and lower layers, with intrusive materials sandwiched between them. In addition, cavities should be expected in the limestone layer.

Superficial deposits of the Kallang Formation (peat, fluvial sand, fluvial clay, marine clay) are encountered at several shaft and tunnel boreholes at and between Shafts O3, O2, O1, N3, and N. Their presence is in general agreement with what is anticipated from the geological map at this location.

The conglomerate of various thicknesses interbedded within sandstone, siltstone bedding is reported in boreholes between Shaft N2 and N3, N-N1/BH-107, Shaft O1, Shaft O2, etc. The conglomerate here is described in logs as Very Weak to Very Strong. The extent of this conglomerate is unknown from the boreholes. The conglomerate could potentially be a rigid material localized or extensive embedded in a comparatively weaker rock bed.

Breccia interbedded within sandstone was encountered at borehole N3-O1/BH-201 between 47.894mRL and 84.894mRL below the tunnel invert horizon. According to EN ISO 14689-1:2003 titled “Aid to rock identification for engineering purposes” these are described as coarse to very coarse-grained cobbles, pebbles, and sharp gravels and sand, etc., under the clastic sedimentary category. The extent of Breccia is unknown from the borehole data.

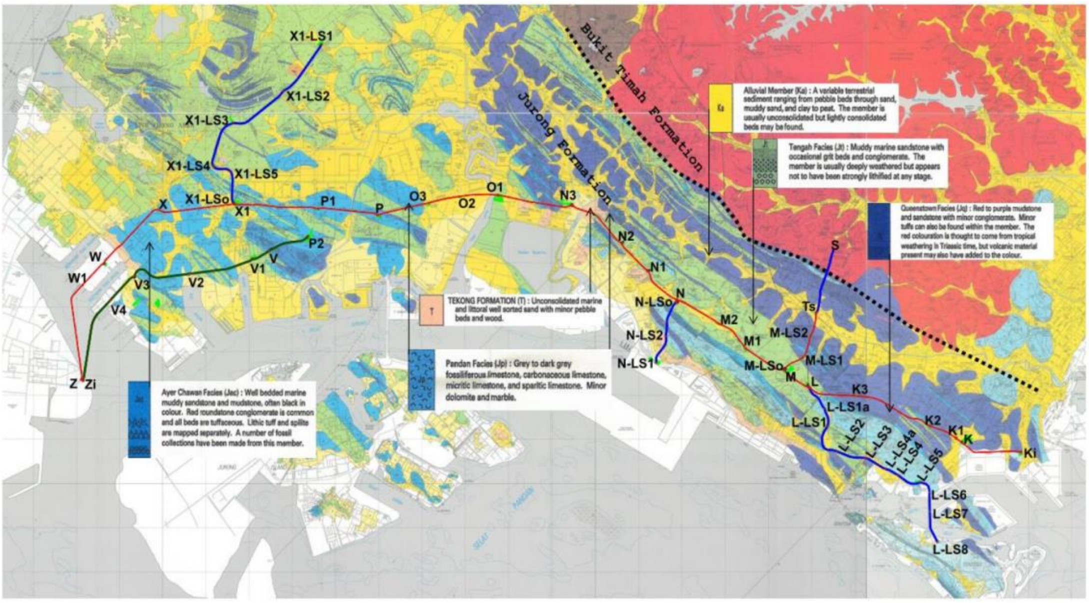


Figure 5-2 Proposed DTSS 2 Alignment including borehole locations and regional geology

5.3 Tunnelling in Mixed Face, Variable and Hard Ground Conditions

The rocks of the Jurong Formation are variably weathered and are complexly interbedded. Subsequent to their deposition and lithification, the rocks have been subjected to intense shearing and faulting by tectonic activity, together with some low-level metamorphism. Because of their variability, bored tunneling through mixed face conditions of soil and rock along the tunnel is to be expected at some locations.

Due to the presence of soil, weak rock, strong rock, and groundwater, the operation of TBMs in a sealed mode and careful control of face pressures will be one of the critical issues. The problems associated with maintaining the required balancing face pressure in mixed face soil/rock conditions must be considered when choosing the most suitable machine type.

The Jurong Formation at moderate depth is often tightly jointed with little presence of flowing water. However, at a shallower depth, the Jurong Formation is more permeable with instances of open joints and fissures capable of resulting in very large rates of inflow into tunnels and deep excavations with a risk of flooding. The potential for high rates of inflow has implications regarding the measures required to ensure the face stability of the tunnels and control water levels around all of the excavations.

Some boreholes have reported core loss that could be solution cavities in limestone, but so far, no DTSS 2 borehole has identified limestone cavities within Contract T-09. The potential of encountering cavities poses a problem during the excavation of diaphragm trenches or bored piles because the support fluid stabilizing the open trenches could leak away through cavities and hence compromising stability. The other potential issue is the significant over-break/ over-consumption of concrete to form the cast-in-situ elements as the discharged concrete could flow into the cavities. Therefore, it is necessary to seal all cavities before any excavation work. Cavities encountered during tunneling could pose a potential problem of stabilization fluid loss resulting in face instability and settlement. Depending on the size of the cavity, it could be difficult to maintain the tunnel alignment when tunneling through limestone formation laced with cavities. Hence when tunneling through zones of suspected cavities, prudent measures of forwarding probing for cavities must be carried out, and any identified cavities shall be sealed either by surface grouting or through the face of TBM.

Based on the stated geological information (Figure 5-4), and difficulties during the tunneling, Herrenknecht Mixhshield TBM with 7.85 m diameter was selected for the T-09 project (Figure 5-3).

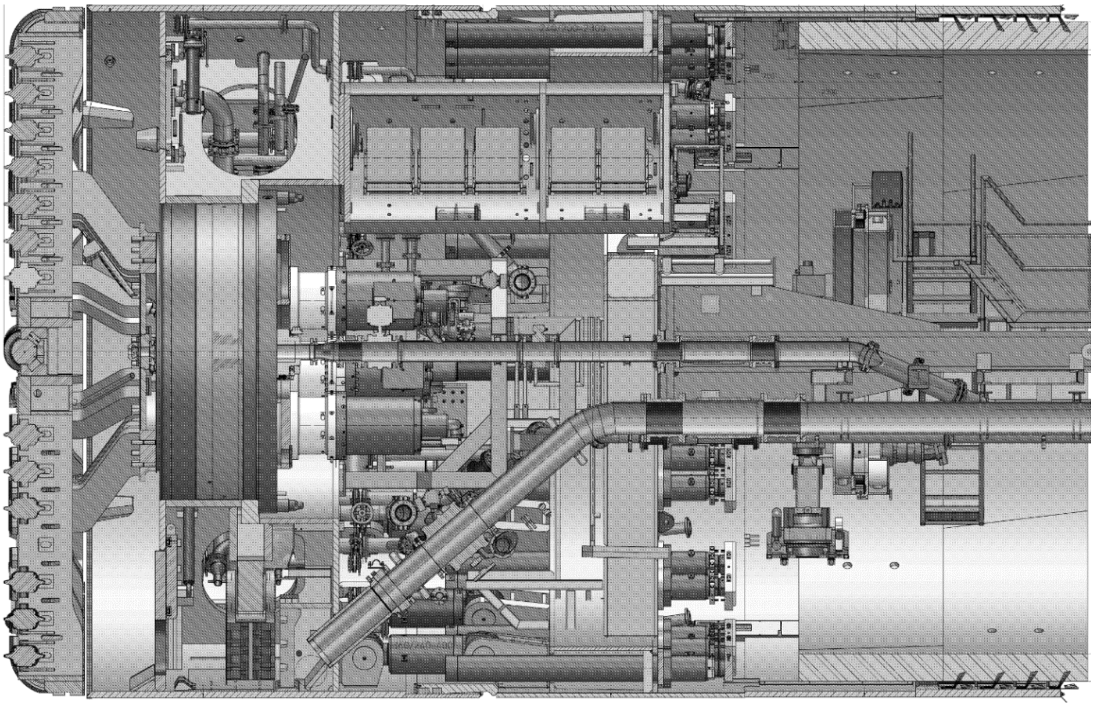


Figure 5-3 Mixshield TBM (Herrenknecht) for T-09 project

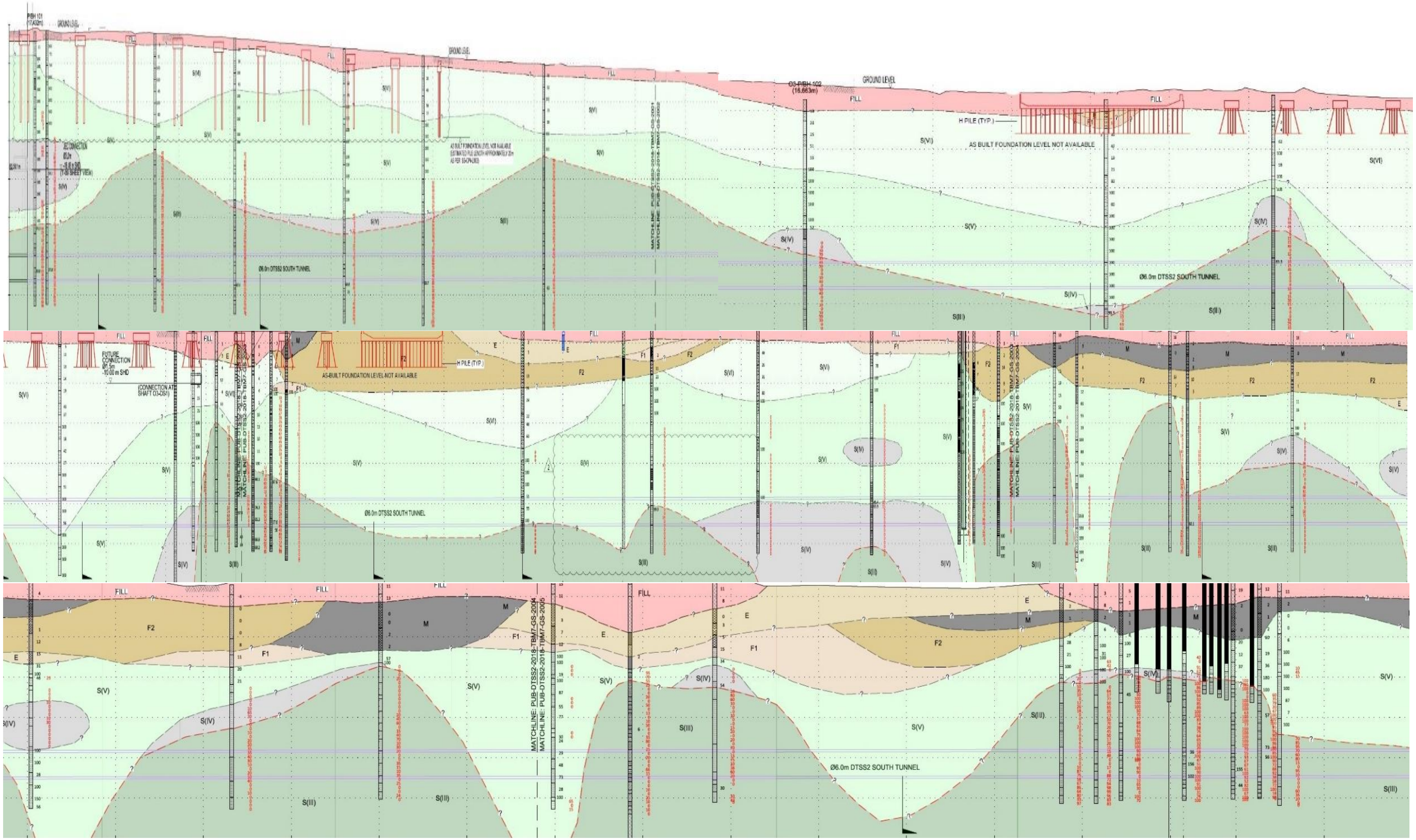


Figure 5-4 Longitudinal profile of T-09 project.

5.4 Input Data

The data to be analyzed in this study are divided into 2 groups. The first group includes the Load, Id and Angle while the second group consists of the operating parameters of the TBM, such as Thrust Force, Torque, Advance Speed, Penetration and Main Drive Speed. The final version of input data has been illustrated in Table 5-2.

Load (N)	ID	Angle	Chainage (m)	Advance Speed (mm/min)	Thrust Force (kN)	MainDrive Speed	Torque	Penetration (mm/rot)
63220	35	1.5207	23435	5.9	24112	1.05	0.636	5.6
33691	28	1.5568	23435	5.9	24112	1.05	0.636	5.6
53100	22	1.5568	23435	5.9	24112	1.05	0.636	5.6
95764	15	1.556	23435	5.9	24112	1.05	0.636	5.6

Table 5-2 Row input data for the analysis (example)

During the TBM advance, thanks to the direct contact between disc cutters that are equipped with sensors, and existing geology sensors record different load value for each encountered point of formation. In addition, since the tunnel face is 360 degree due to the general shape, the angle value illustrates the location of sensors during the rotation of cutterhead.

Another important parameter is the radar image recorded for different date/time and for each 10 cm penetration. These images will be used to validate (approximately) 3D and 2D models that will be developed based on the load, chainage and angle (Figure 5-5).

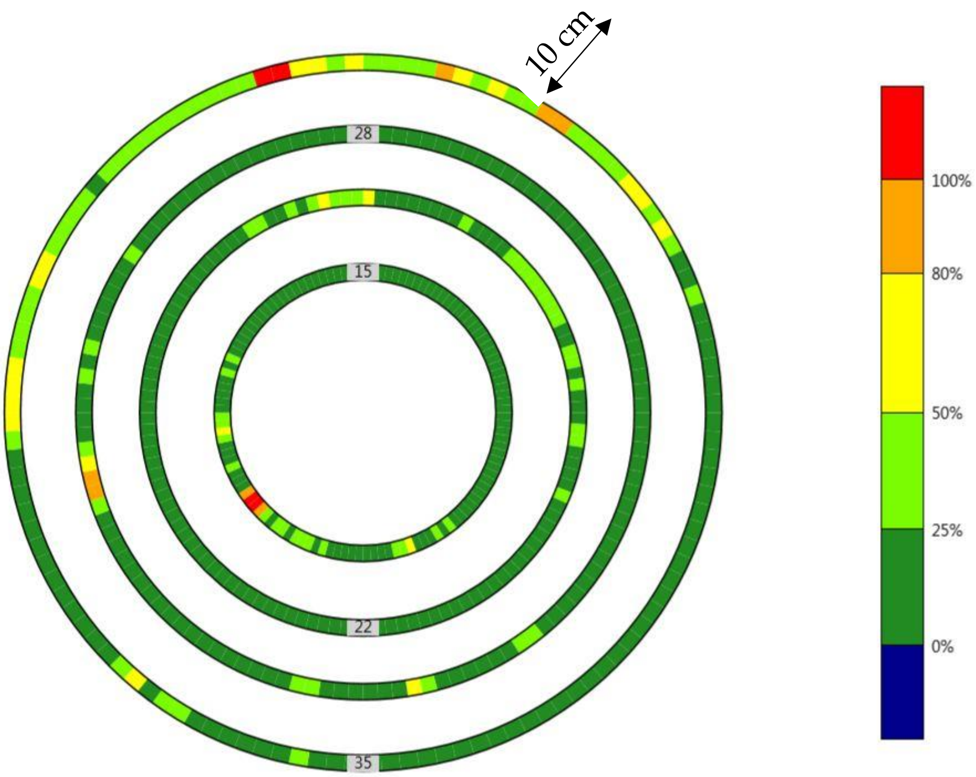


Figure 5-5 Radar image of DCLM from 31.01.2020 (09:25:56) to 31.01.2020 (14:33:57)

Chapter 6

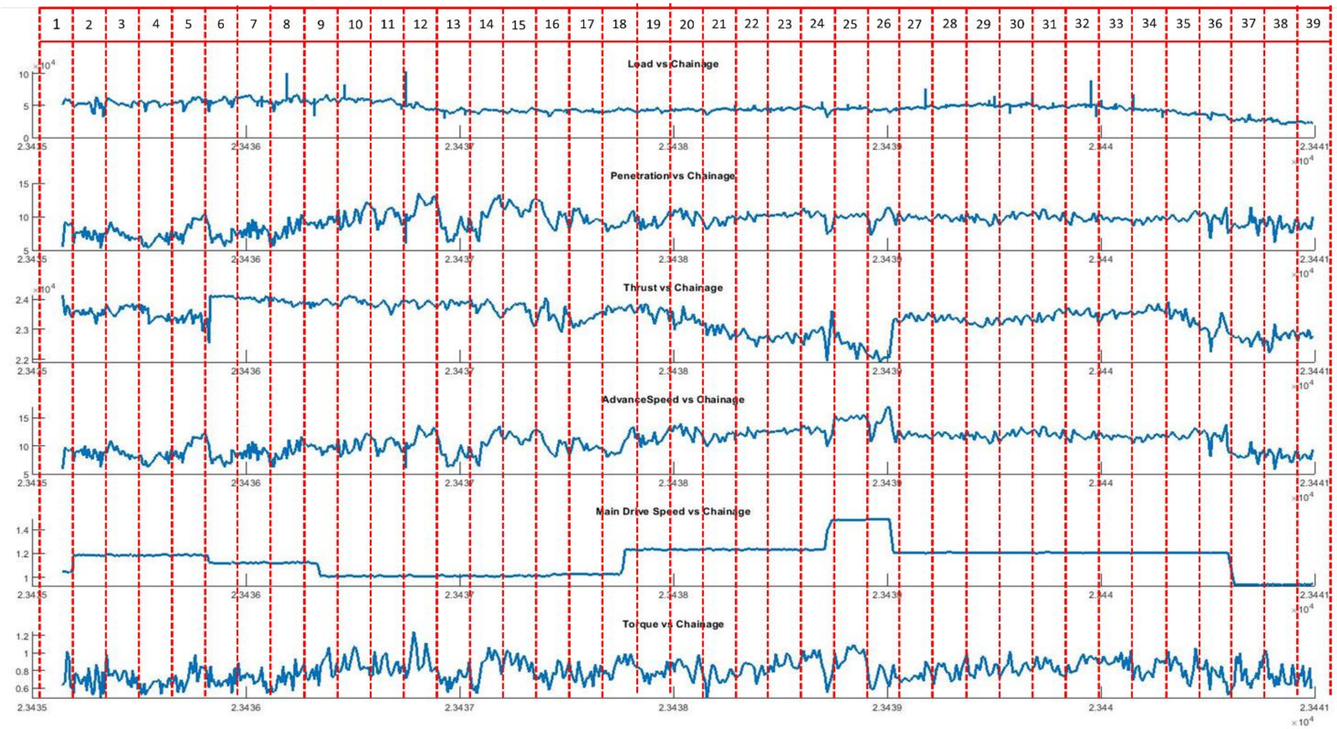
6 Regression Analysis and Modelling

As it is introduced in the 1.2, the main purpose in this research is to reveal the connection between load (DCLM) and TBM operation paramteres (torque, thrust force, advance speed, main drive speed, penetration rate). In this context both visual and mathematical correlation analysis conducted. Generally, to actualize all the steps of research MATLAB, SPSS and Python were utilized.

6.1 Visual Correlation Analysis

Correlation analysis is a statistical method used to determine whether there is a relationship between the two variables, and if so, in which direction and to what extent. In addition to mathematical correlation, visual correlation can also be performed to see if there are any similarities between the plots so that special groups of data can be selected for the next mathematical analysis.

Initially, all data were divided into two part, and the analysis done for each half. In addition, the plots were divided into the equally sized vertical sections where each section had a specific ID number. Due to the complex visual, the second half was not analyzed individually, but specific ranges were selected for both half and plotted in order to see the correlation in more detail. Since there was not a valid way to quantify the quality of correlation, a new color scale, which composed of different colors showing the different quality of correlation, was established (From Figure 6-1 to Figure 6-9).

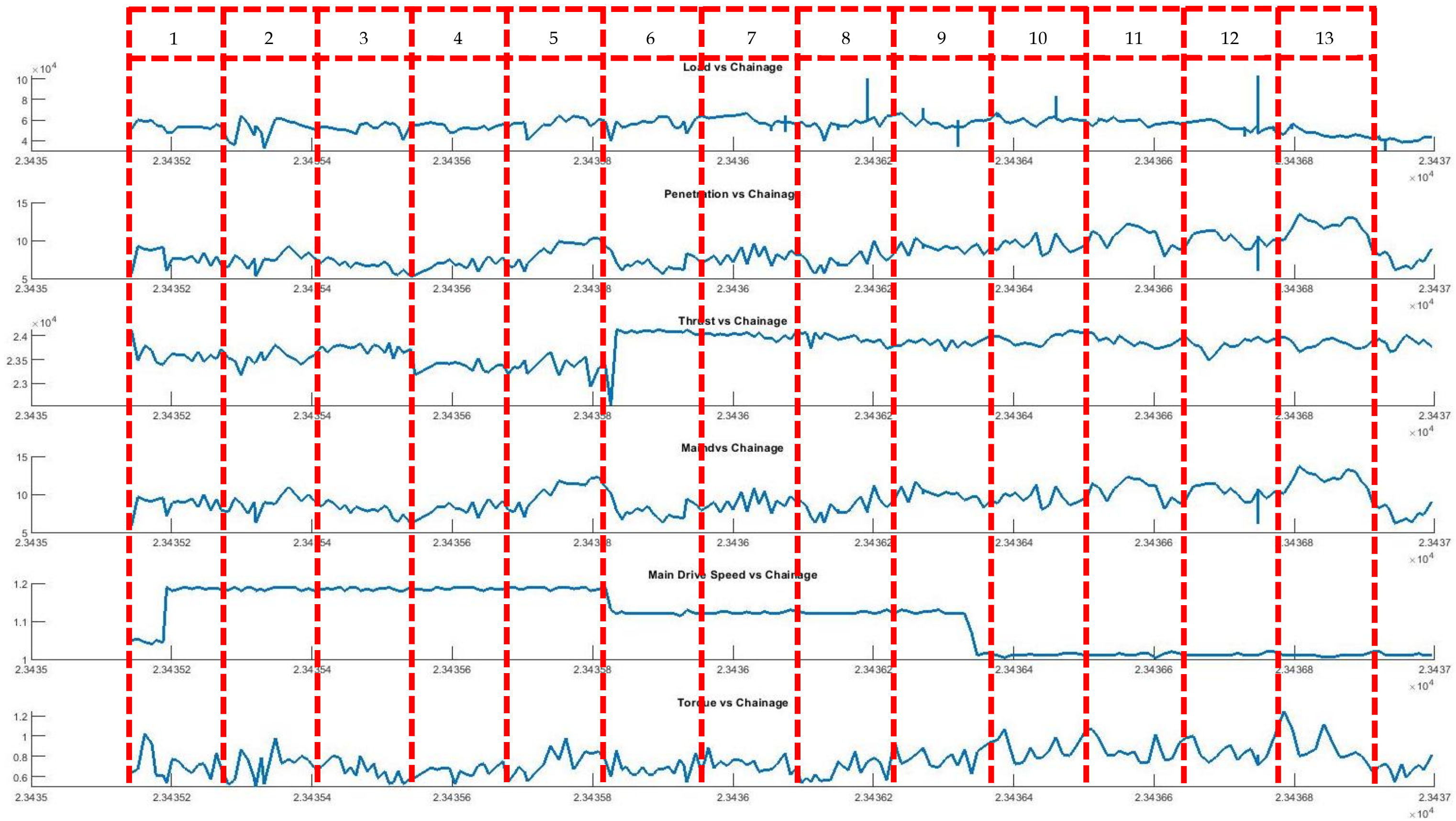


1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque
10	Load	Penetration	Thrust	Speed A	SpeedM	Torque
11	Load	Penetration	Thrust	Speed A	SpeedM	Torque
12	Load	Penetration	Thrust	Speed A	SpeedM	Torque
13	Load	Penetration	Thrust	Speed A	SpeedM	Torque
14	Load	Penetration	Thrust	Speed A	SpeedM	Torque
15	Load	Penetration	Thrust	Speed A	SpeedM	Torque
16	Load	Penetration	Thrust	Speed A	SpeedM	Torque
17	Load	Penetration	Thrust	Speed A	SpeedM	Torque
18	Load	Penetration	Thrust	Speed A	SpeedM	Torque
19	Load	Penetration	Thrust	Speed A	SpeedM	Torque
20	Load	Penetration	Thrust	Speed A	SpeedM	Torque

21	Load	Penetration	Thrust	Speed A	SpeedM	Torque
22	Load	Penetration	Thrust	Speed A	SpeedM	Torque
23	Load	Penetration	Thrust	Speed A	SpeedM	Torque
24	Load	Penetration	Thrust	Speed A	SpeedM	Torque
25	Load	Penetration	Thrust	Speed A	SpeedM	Torque
26	Load	Penetration	Thrust	Speed A	SpeedM	Torque
27	Load	Penetration	Thrust	Speed A	SpeedM	Torque
28	Load	Penetration	Thrust	Speed A	SpeedM	Torque
29	Load	Penetration	Thrust	Speed A	SpeedM	Torque
30	Load	Penetration	Thrust	Speed A	SpeedM	Torque
31	Load	Penetration	Thrust	Speed A	SpeedM	Torque
32	Load	Penetration	Thrust	Speed A	SpeedM	Torque
33	Load	Penetration	Thrust	Speed A	SpeedM	Torque
34	Load	Penetration	Thrust	Speed A	SpeedM	Torque
35	Load	Penetration	Thrust	Speed A	SpeedM	Torque
36	Load	Penetration	Thrust	Speed A	SpeedM	Torque
37	Load	Penetration	Thrust	Speed A	SpeedM	Torque
38	Load	Penetration	Thrust	Speed A	SpeedM	Torque
39	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

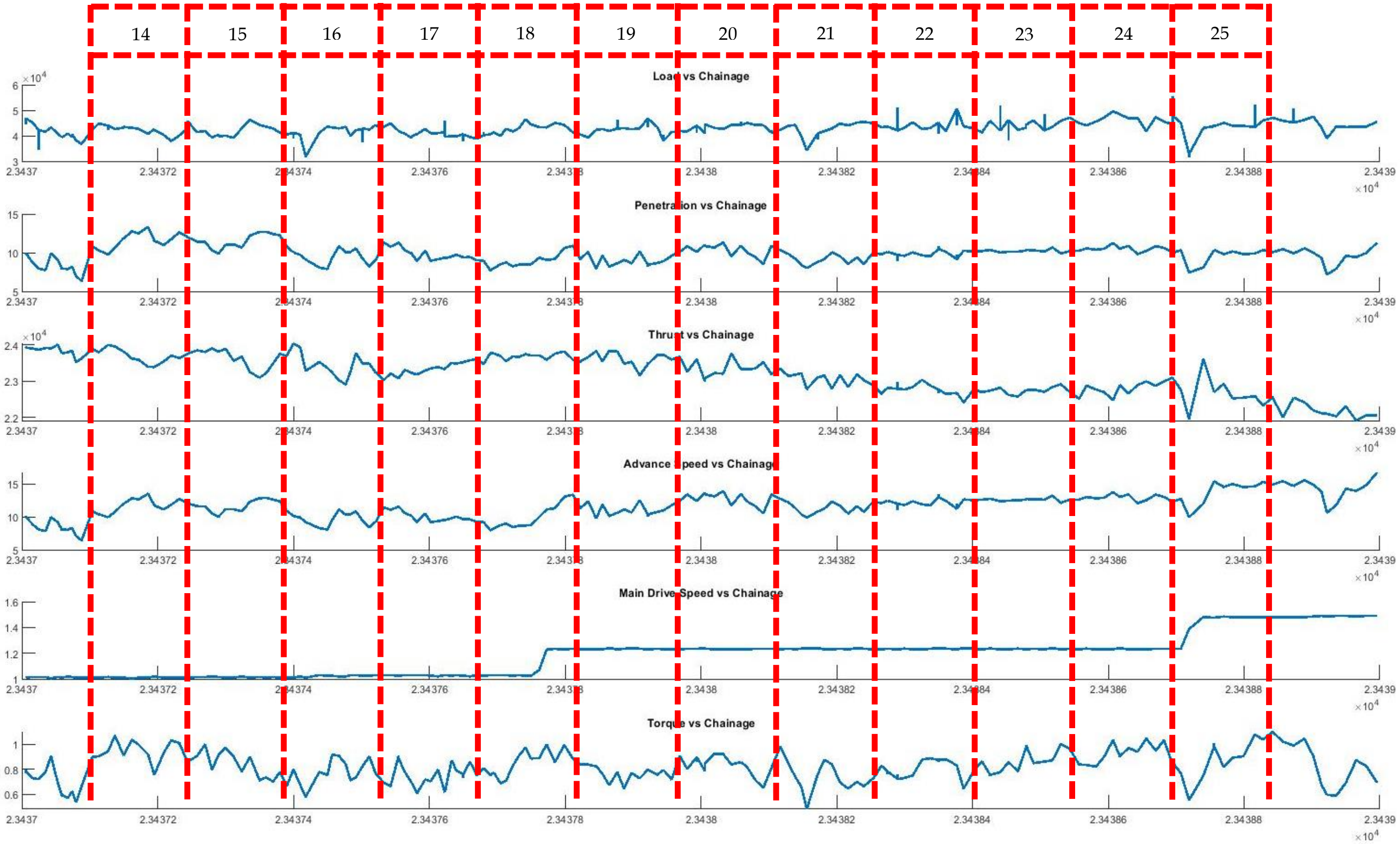
Figure 6-1 Visual Correlation analysis for the first half of data



1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque
10	Load	Penetration	Thrust	Speed A	SpeedM	Torque
11	Load	Penetration	Thrust	Speed A	SpeedM	Torque
12	Load	Penetration	Thrust	Speed A	SpeedM	Torque
13	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

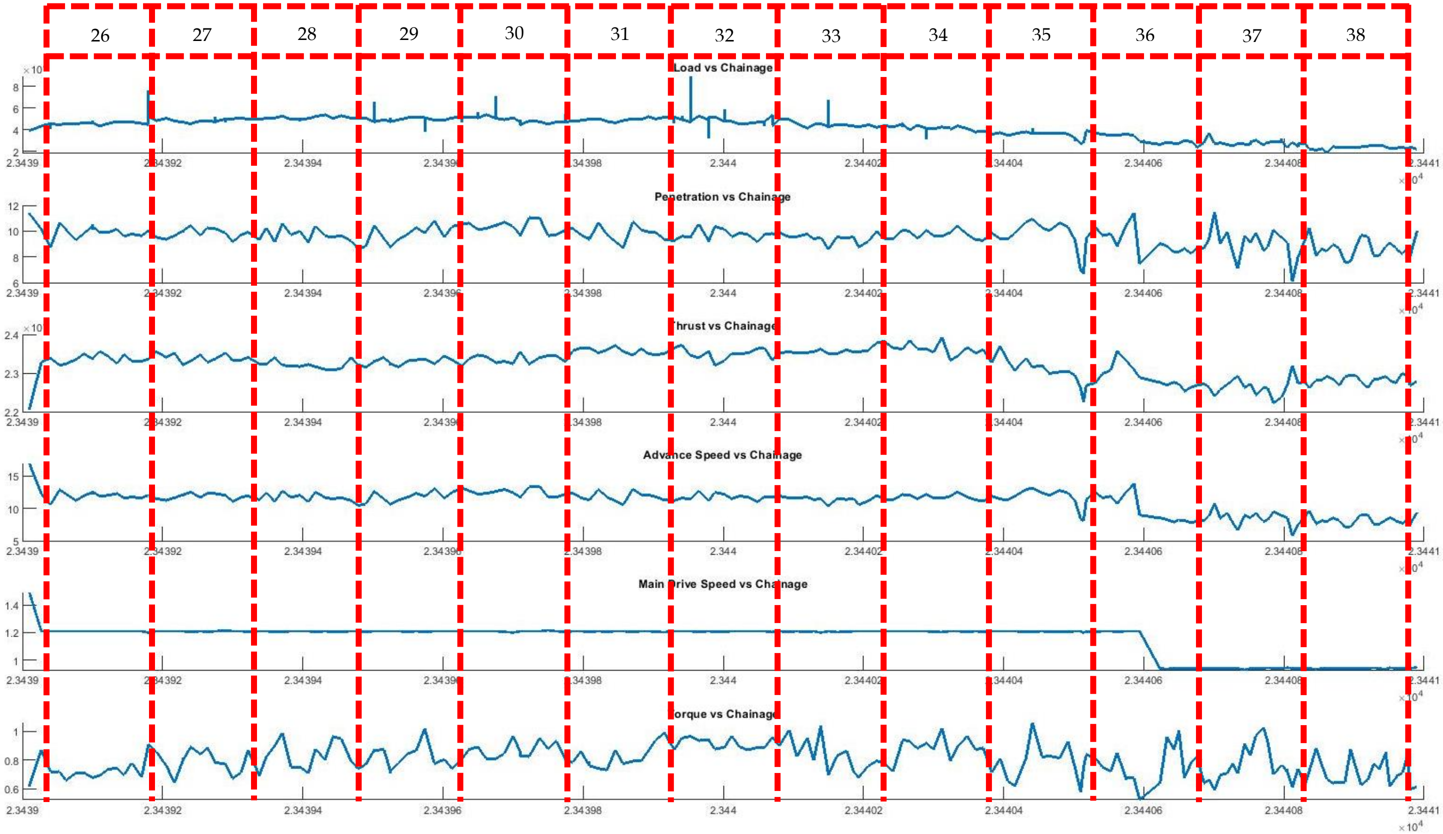
Figure 6-2 Visual Correlation for data between the chainage 23435 (m) and 23437 (m)



14	Load	Penetration	Thrust	Speed A	SpeedM	Torque
15	Load	Penetration	Thrust	Speed A	SpeedM	Torque
16	Load	Penetration	Thrust	Speed A	SpeedM	Torque
17	Load	Penetration	Thrust	Speed A	SpeedM	Torque
18	Load	Penetration	Thrust	Speed A	SpeedM	Torque
19	Load	Penetration	Thrust	Speed A	SpeedM	Torque
20	Load	Penetration	Thrust	Speed A	SpeedM	Torque
21	Load	Penetration	Thrust	Speed A	SpeedM	Torque
22	Load	Penetration	Thrust	Speed A	SpeedM	Torque
23	Load	Penetration	Thrust	Speed A	SpeedM	Torque
24	Load	Penetration	Thrust	Speed A	SpeedM	Torque
25	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

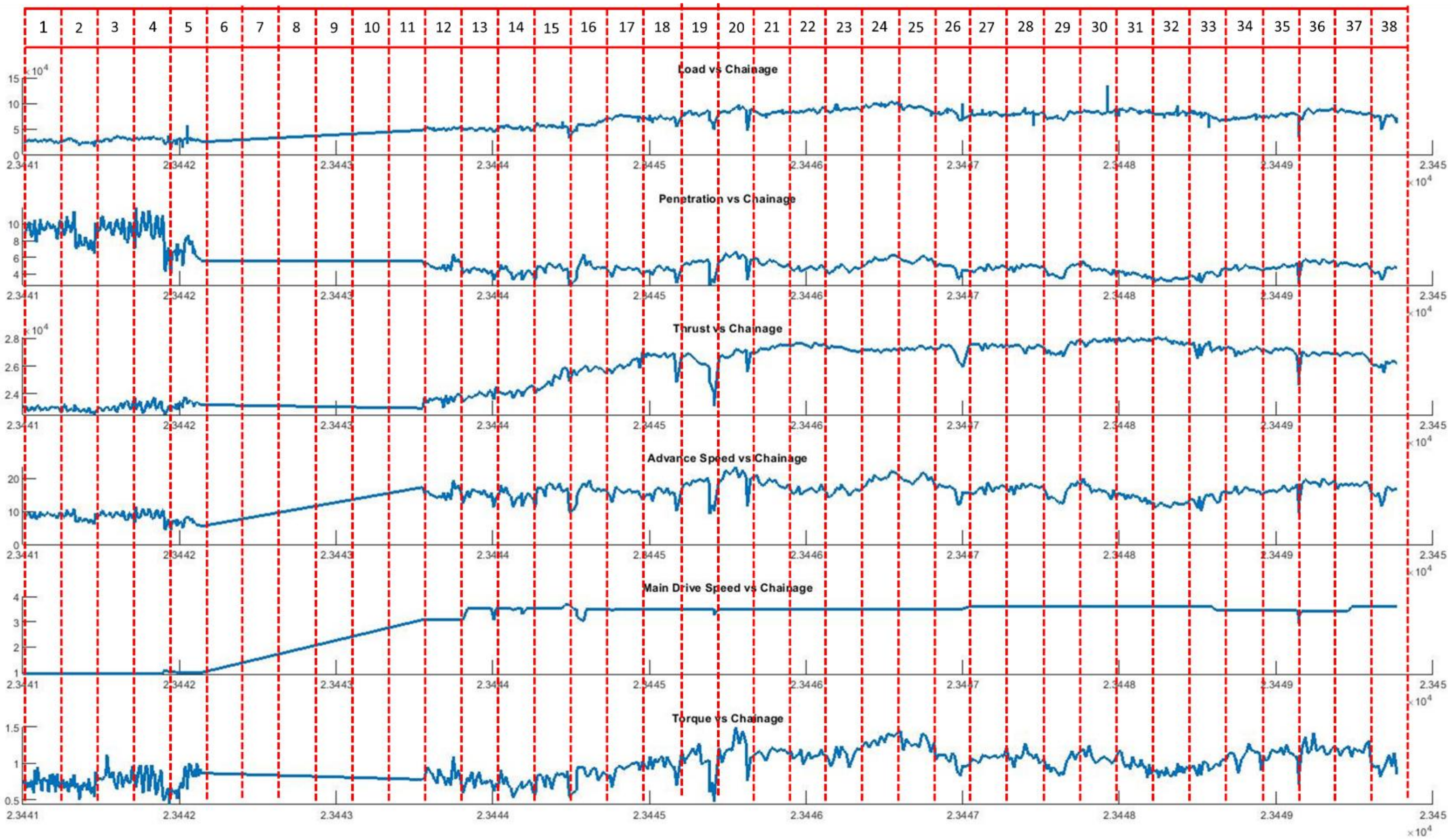
Figure 6-3 Visual Correlation for data between the chainage 23437 (m) and 23439(m)



26	Load	Penetration	Thrust	Speed A	SpeedM	Torque
27	Load	Penetration	Thrust	Speed A	SpeedM	Torque
28	Load	Penetration	Thrust	Speed A	SpeedM	Torque
29	Load	Penetration	Thrust	Speed A	SpeedM	Torque
30	Load	Penetration	Thrust	Speed A	SpeedM	Torque
31	Load	Penetration	Thrust	Speed A	SpeedM	Torque
32	Load	Penetration	Thrust	Speed A	SpeedM	Torque
33	Load	Penetration	Thrust	Speed A	SpeedM	Torque
34	Load	Penetration	Thrust	Speed A	SpeedM	Torque
35	Load	Penetration	Thrust	Speed A	SpeedM	Torque
36	Load	Penetration	Thrust	Speed A	SpeedM	Torque
37	Load	Penetration	Thrust	Speed A	SpeedM	Torque
38	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

Figure 6-4 Visual Correlation for data between the chainage 23439 (m) and 23441 (m)

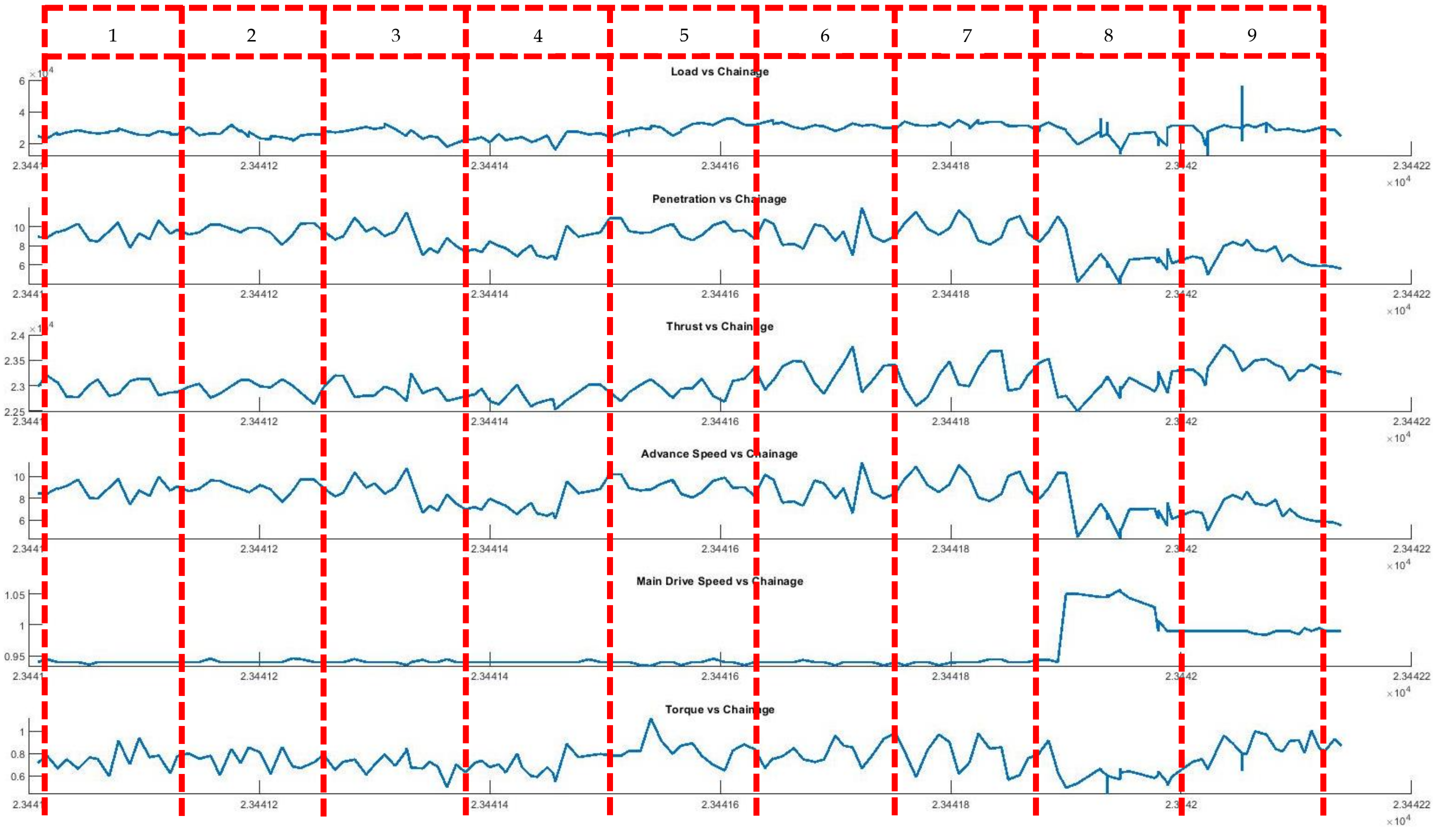


1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque
10	Load	Penetration	Thrust	Speed A	SpeedM	Torque
11	Load	Penetration	Thrust	Speed A	SpeedM	Torque
12	Load	Penetration	Thrust	Speed A	SpeedM	Torque
13	Load	Penetration	Thrust	Speed A	SpeedM	Torque
14	Load	Penetration	Thrust	Speed A	SpeedM	Torque
15	Load	Penetration	Thrust	Speed A	SpeedM	Torque
16	Load	Penetration	Thrust	Speed A	SpeedM	Torque
17	Load	Penetration	Thrust	Speed A	SpeedM	Torque
18	Load	Penetration	Thrust	Speed A	SpeedM	Torque
19	Load	Penetration	Thrust	Speed A	SpeedM	Torque
20	Load	Penetration	Thrust	Speed A	SpeedM	Torque

21	Load	Penetration	Thrust	Speed A	SpeedM	Torque
22	Load	Penetration	Thrust	Speed A	SpeedM	Torque
23	Load	Penetration	Thrust	Speed A	SpeedM	Torque
24	Load	Penetration	Thrust	Speed A	SpeedM	Torque
25	Load	Penetration	Thrust	Speed A	SpeedM	Torque
26	Load	Penetration	Thrust	Speed A	SpeedM	Torque
27	Load	Penetration	Thrust	Speed A	SpeedM	Torque
28	Load	Penetration	Thrust	Speed A	SpeedM	Torque
29	Load	Penetration	Thrust	Speed A	SpeedM	Torque
30	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

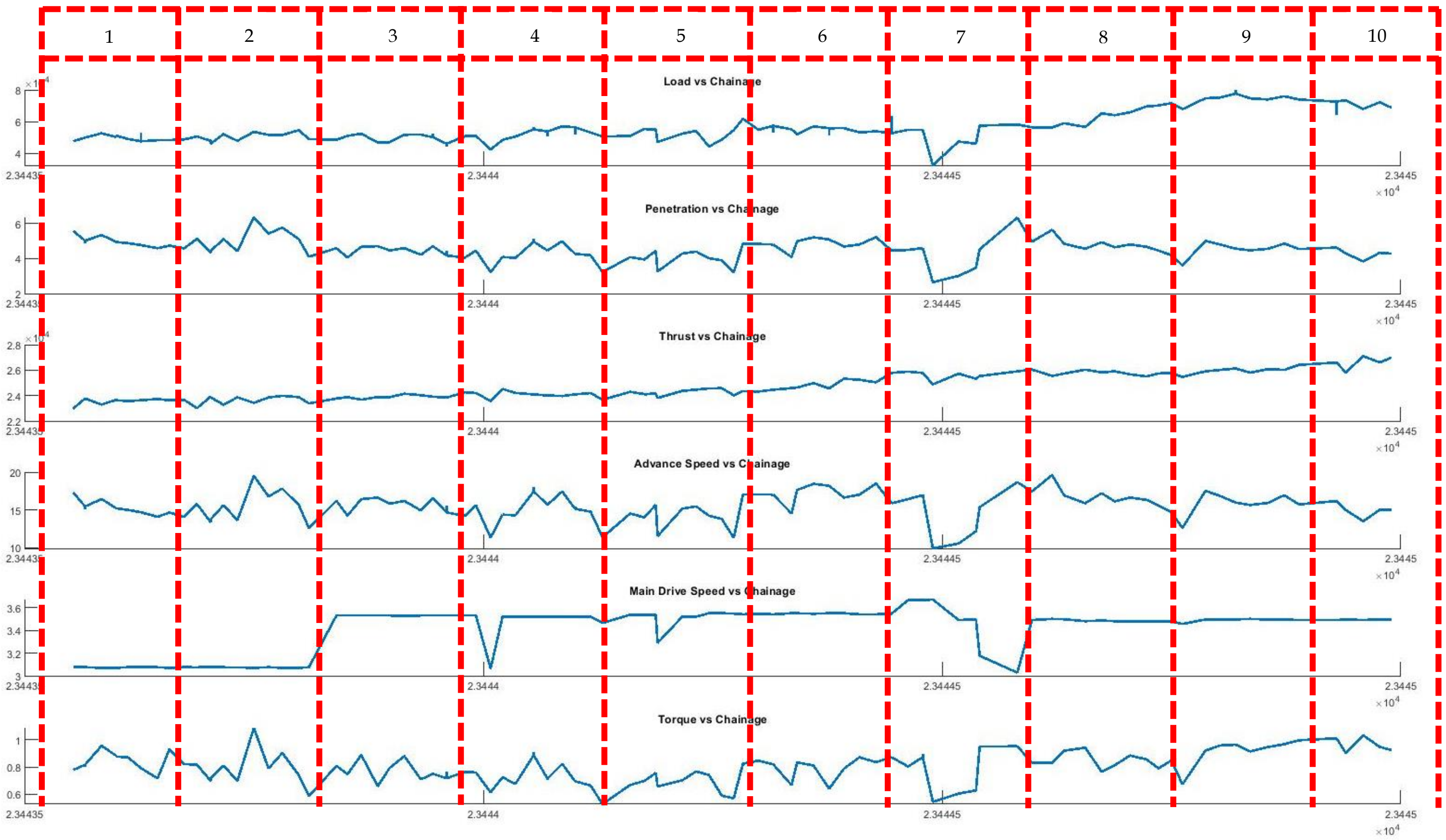
Figure 6-5 Visual Correlation for the second half of data



1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

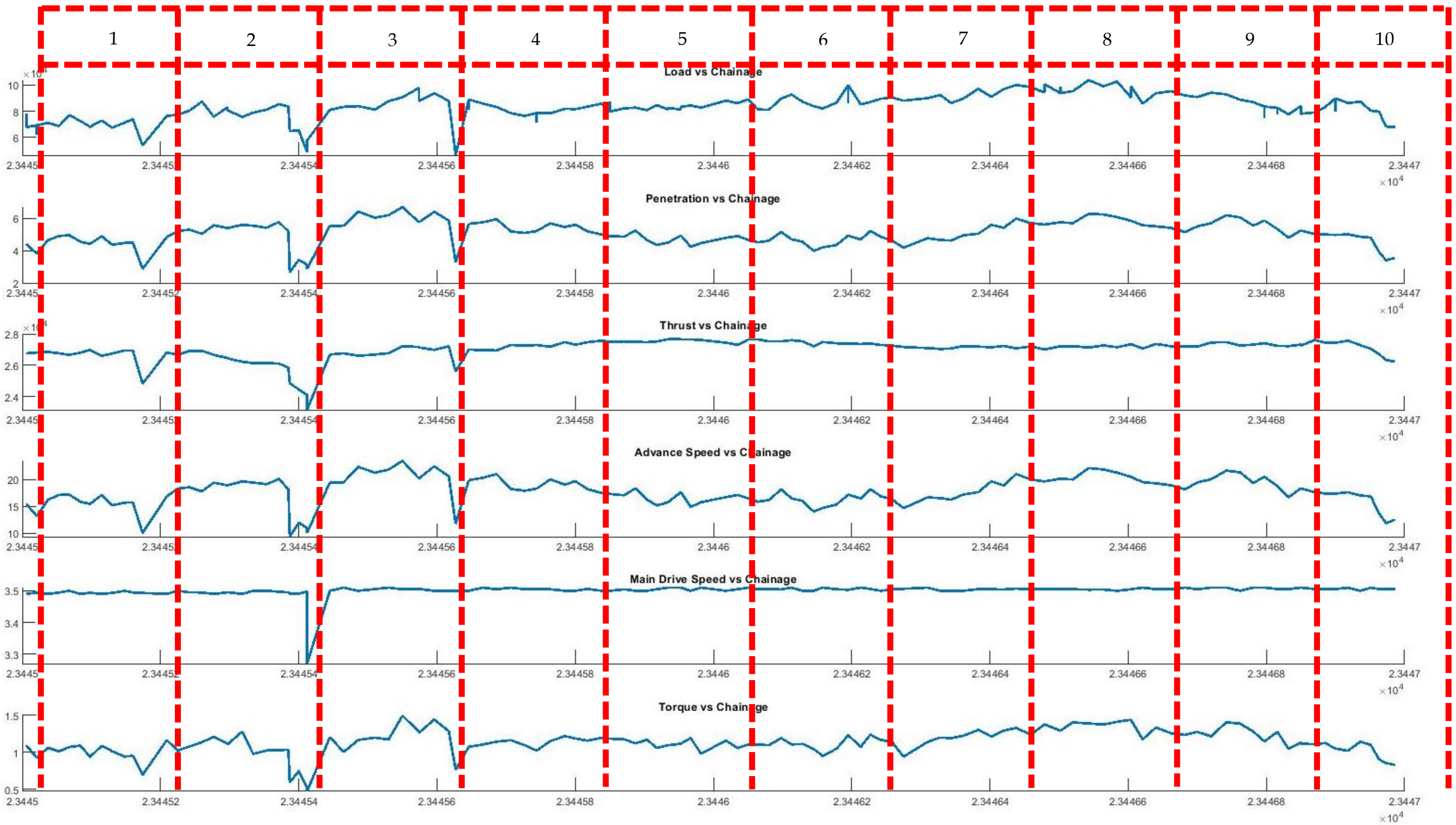
Figure 6-6 Visual Correlation for data between the chainage 23441 (m) and23443(m)



1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque
10	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

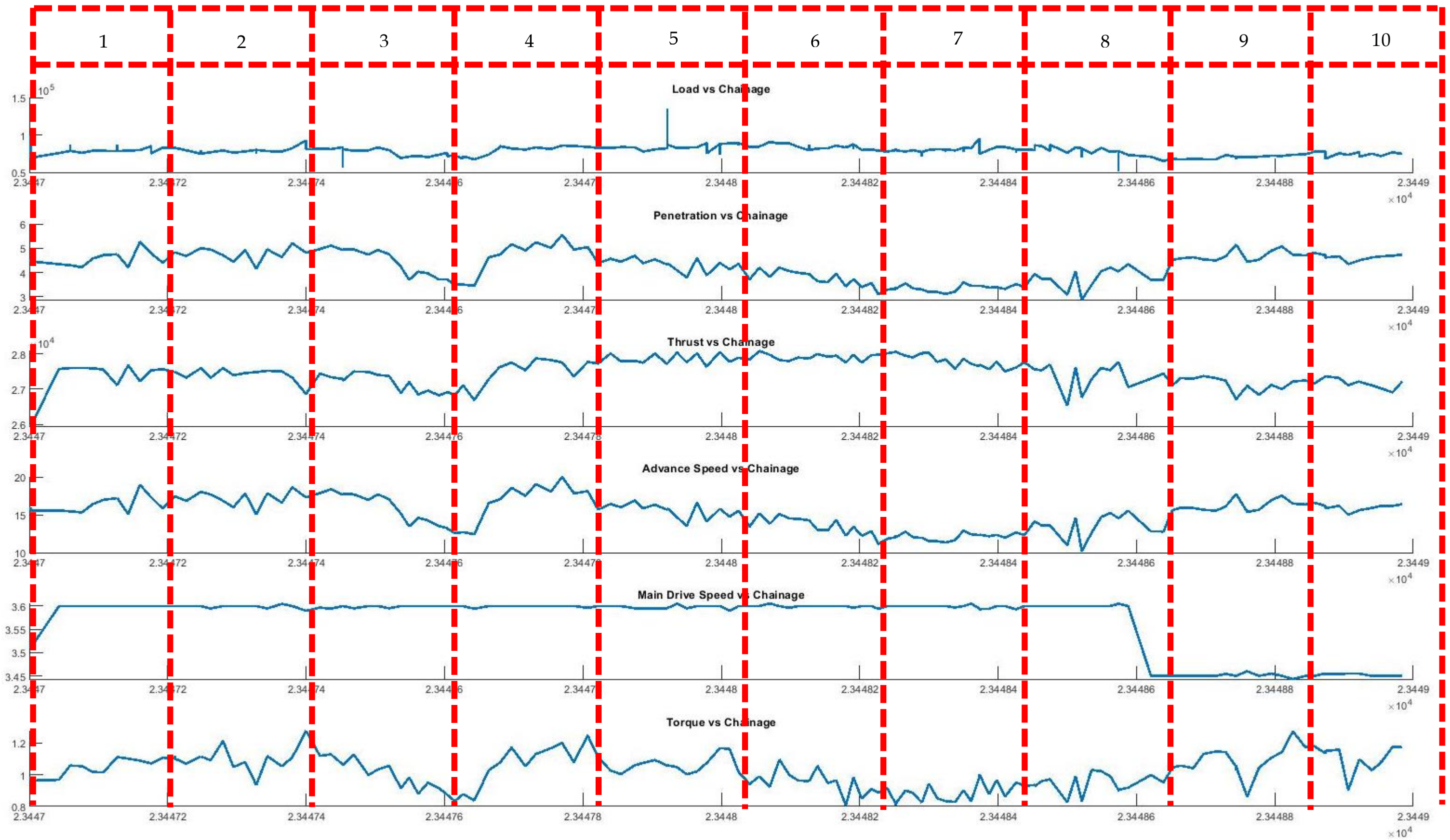
Figure 6-7 Visual Correlation for data between the chainage23445 (m) and 23447 (m)



1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque
10	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

Figure 6-8 Visual Correlation for data between the chainage 23445 (m) and 23447 (m)



1	Load	Penetration	Thrust	Speed A	SpeedM	Torque
2	Load	Penetration	Thrust	Speed A	SpeedM	Torque
3	Load	Penetration	Thrust	Speed A	SpeedM	Torque
4	Load	Penetration	Thrust	Speed A	SpeedM	Torque
5	Load	Penetration	Thrust	Speed A	SpeedM	Torque
6	Load	Penetration	Thrust	Speed A	SpeedM	Torque
7	Load	Penetration	Thrust	Speed A	SpeedM	Torque
8	Load	Penetration	Thrust	Speed A	SpeedM	Torque
9	Load	Penetration	Thrust	Speed A	SpeedM	Torque
10	Load	Penetration	Thrust	Speed A	SpeedM	Torque

Good
Satisfactory
Fair
Poor
No Correlation

Figure 6-9 Visual Correlation for data between the chainage 23447 (m) and 23449 (m)

6.2 Mathematical Correlation Analysis

After filtering the raw data in visual correlation, it was determined that the rest of the analysis would be done for Advance Speed, Thrust Force, Penetration, and Load. Firstly, linear regression analysis was conducted, and the R-square value was evaluated for the selected raw data. R-square is a measure of fit for linear regression models where it describes the strength of the link between the model and the dependent variable. In the linear regression model, the principal intention is to determine how the model fits the data. R square is always between 0-100 % and evaluated by using $R^2 = \frac{Variance\ explanied\ by\ the\ model}{Total\ variance}$.

In addition, the strength of the relationship can be identified based on the distribution of scatter points around the regression line. For instance, in Figure 6-10, the R-square value for the regression model on the left is 15%, and on the right is 85%.

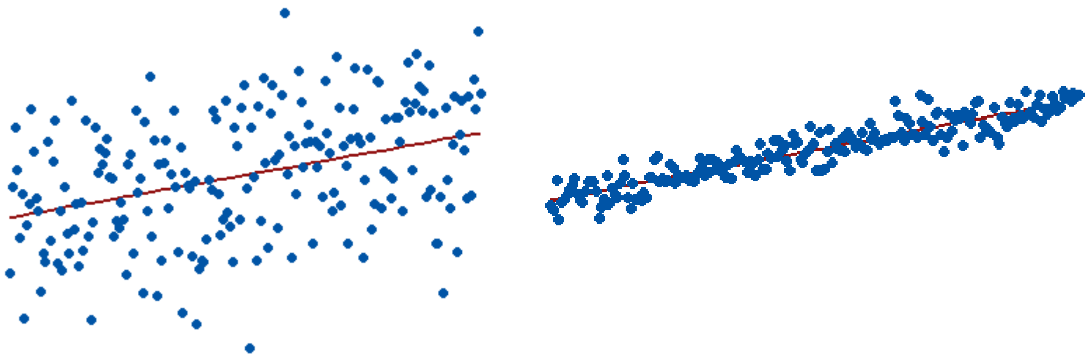


Figure 6-10 Two types of sccatter distribution in regression analysis

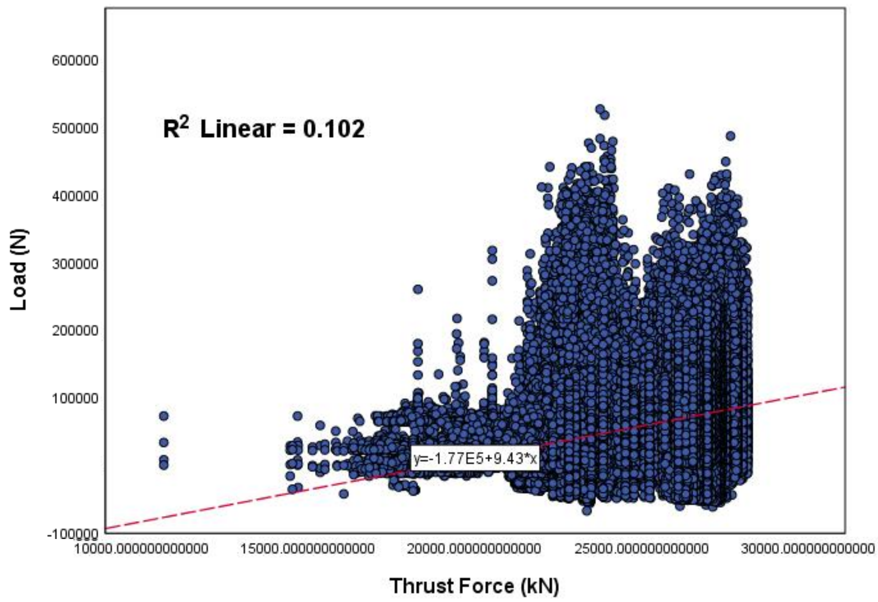


Figure 6-11 Linear Regression analysis between Load (DCLM) and Thrust Force (TBM) (All Data)

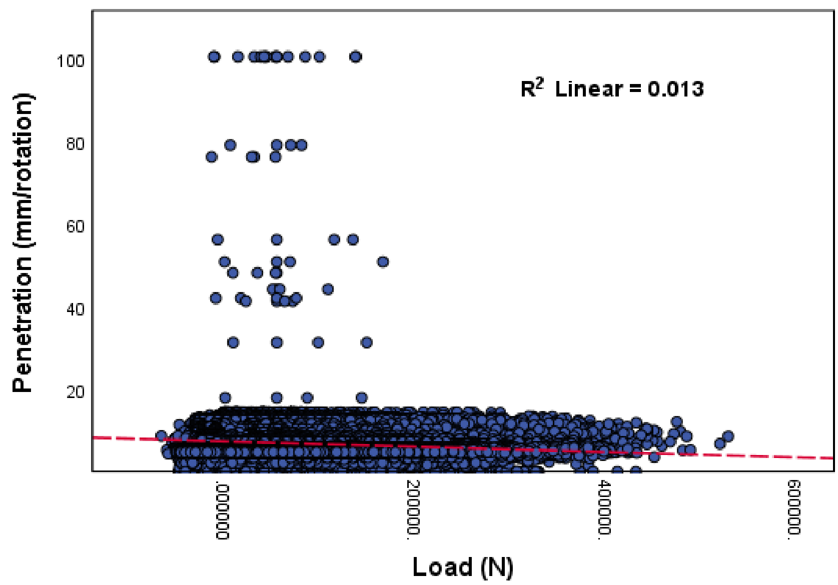


Figure 6-12 Linear Regression analysis between Load (DCLM) and Penetration (TBM) (All Data)

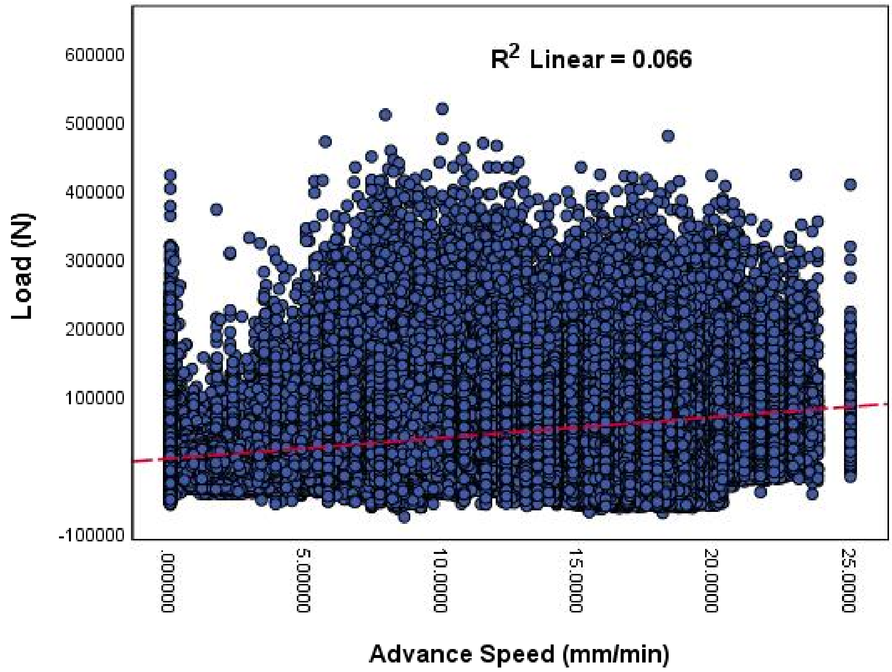


Figure 6-13 Linear Regression analtsis between Load (DCLM) and Advance Speed (TBM) (All Data)

The first linear regression analysis, for row data, results, illustrate that there is not a sufficient correlation between DCLM and TBM data; for instance, in Figure 6-11, the distribution of scatter points around the linear line indicates the weakness of the relationship. The possible reasons for this may be the use of data from all tracks as a single input or technological malfunctions in the DCLM system while data is being collected. Therefore, the data will go through a certain preparation process before performing the linear regression analysis in the next section.

6.3 Development of Correlation Analysis

6.3.1 Analysis of Individual Track

As it is specified in the previous section, one of the reasons for low correlation could be the input data since it consisted of a mixture of all tracks data. Due to this, the main data was filtered based on the track Id, and linear regression was applied again (from Figure 6-14 to Figure 6-25). However, as can be recognized from the figures, no increase in correlation was detected. This indicates that input data necessitates to be re-checked and cleared of errors or arranged in a way that can provide satisfactory results.

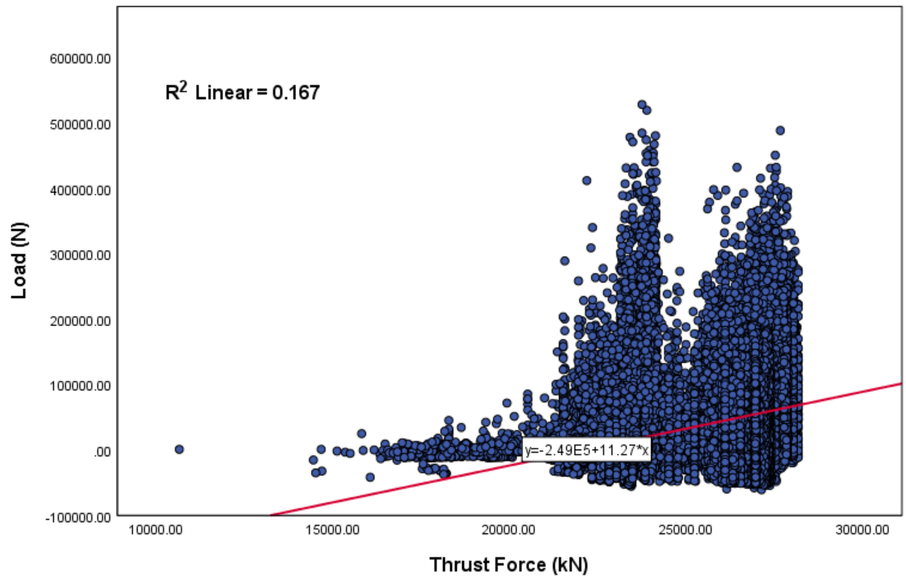


Figure 6-14 Linear Regression analysis between Load (DCLM) and Thrust Force (TBM) for Track 15

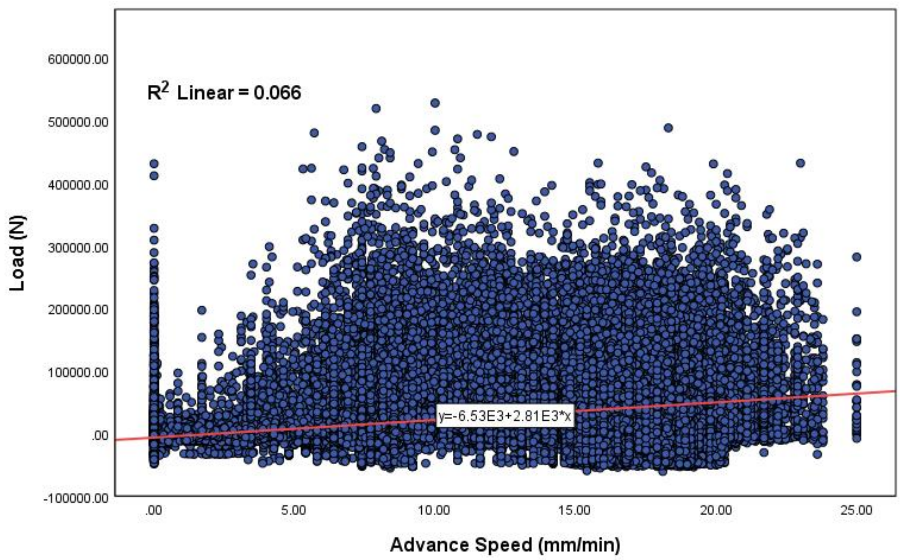


Figure 6-15 Linear Regression analysis between Load (DCLM) and Advance Speed (TBM) for Track 15

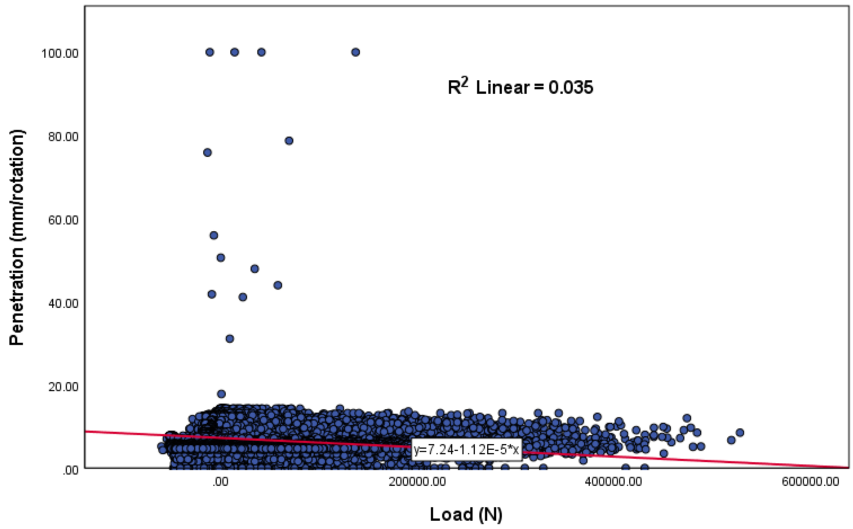


Figure 6-16 Linear Regression analysis between Load (DCLM) and Penetration (TBM) for Track 15

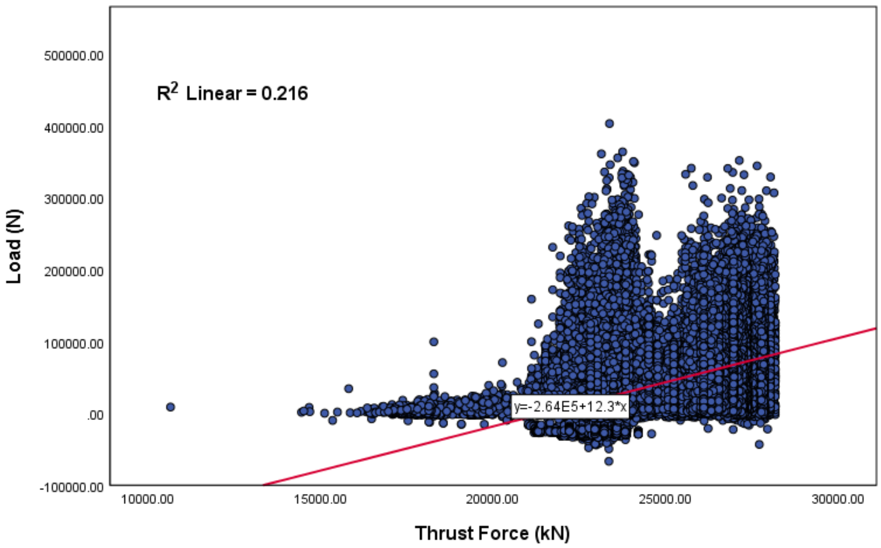


Figure 6-17 Linear Regression analysis between Load (DCLM) and Thrust Force (TBM) for Track 22

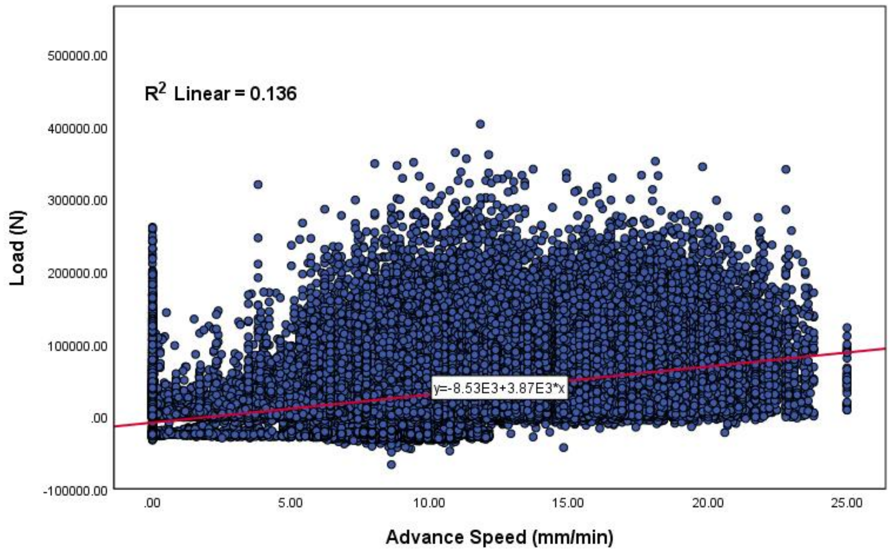


Figure 6-18 Linear Regression analysis between Load (DCLM) and Advance Speed (TBM) for Track 22

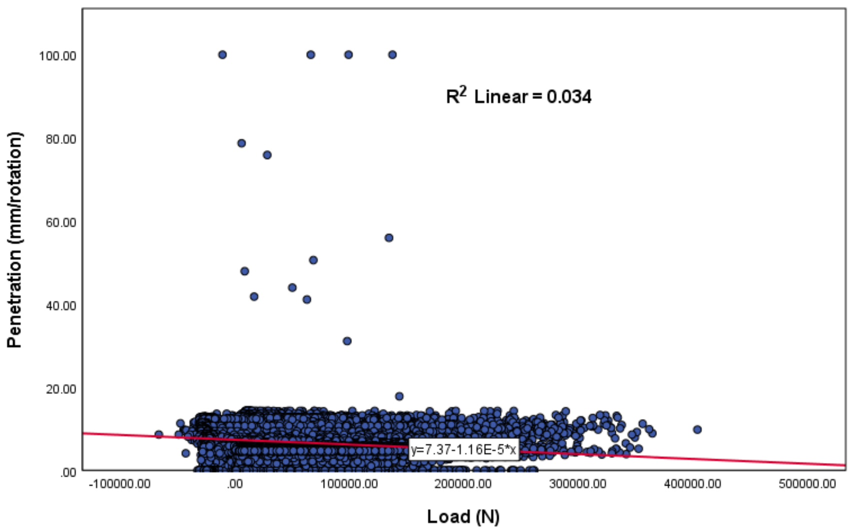


Figure 6-19 Linear Regression analysis between Load (DCLM) and Penetration (TBM) for Track 22

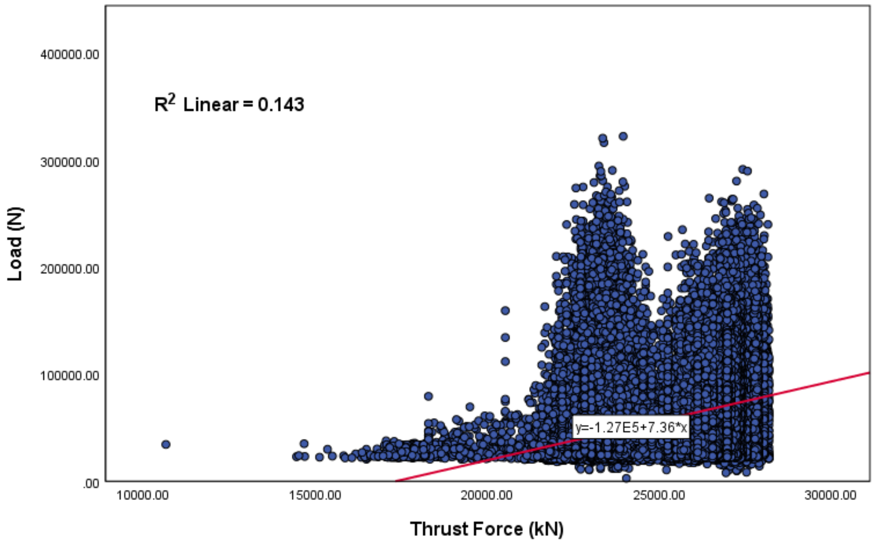


Figure 6-20 Linear Regression analysis between Load (DCLM) and Thrust Force (TBM) for Track 28

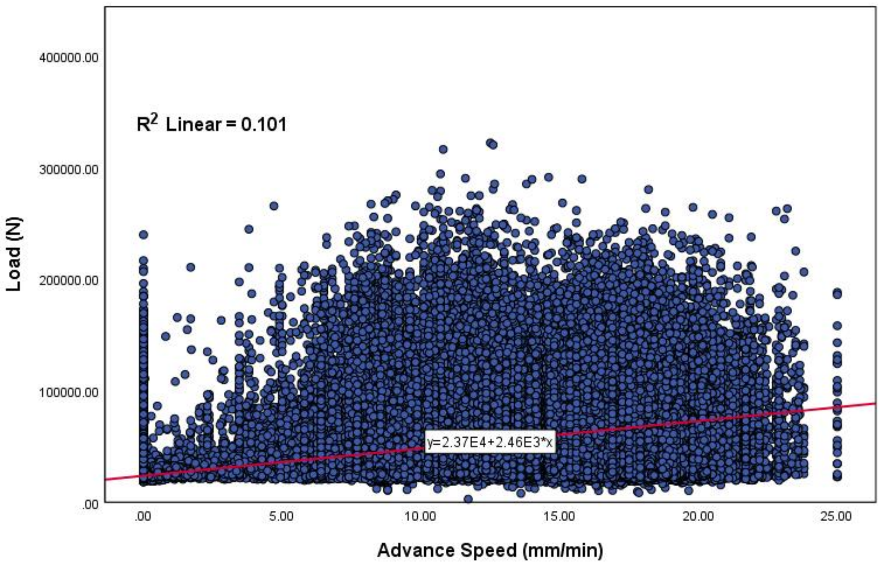


Figure 6-21 Linear Regression analysis between Load (DCLM) and Advance Speed (TBM) for Track 28

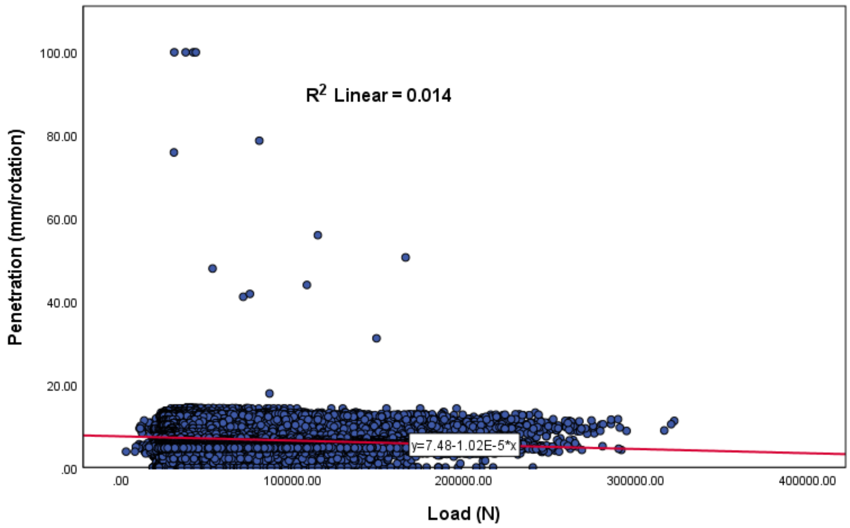


Figure 6-22 Linear Regression analysis between Load (DCLM) and Penetration (TBM) for Track 28

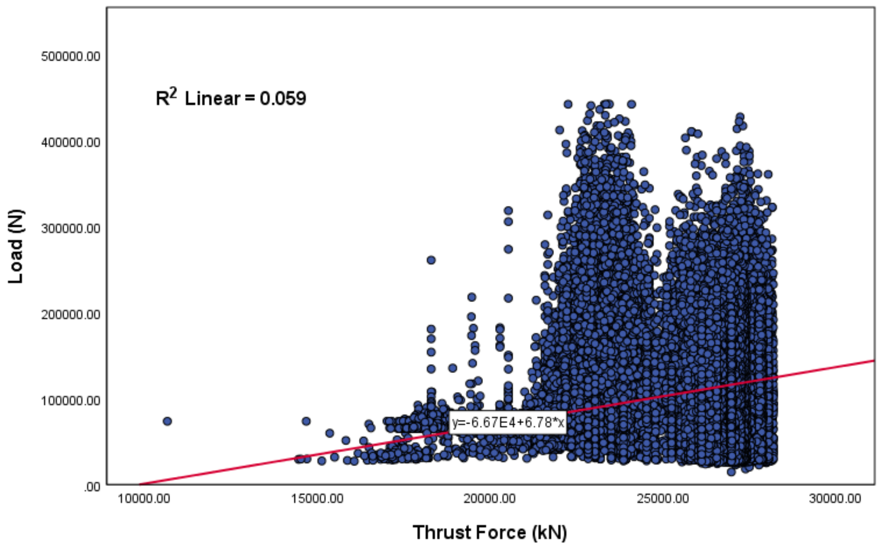


Figure 6-23 Linear Regression analysis between Load (DCLM) and Thrust Force (TBM) for Track 35

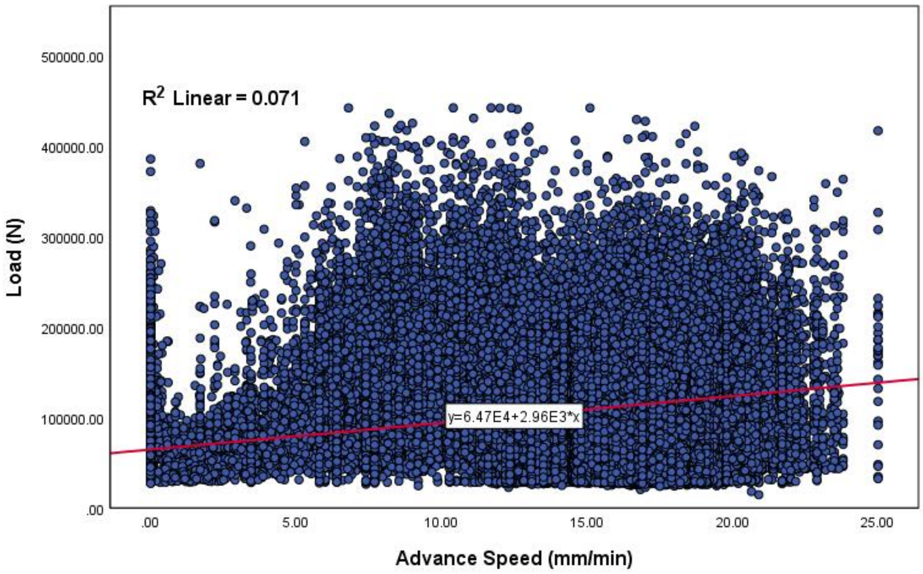


Figure 6-24 Linear Regression analysis between Load (DCLM) and Advance Speed (TBM) for Track 35

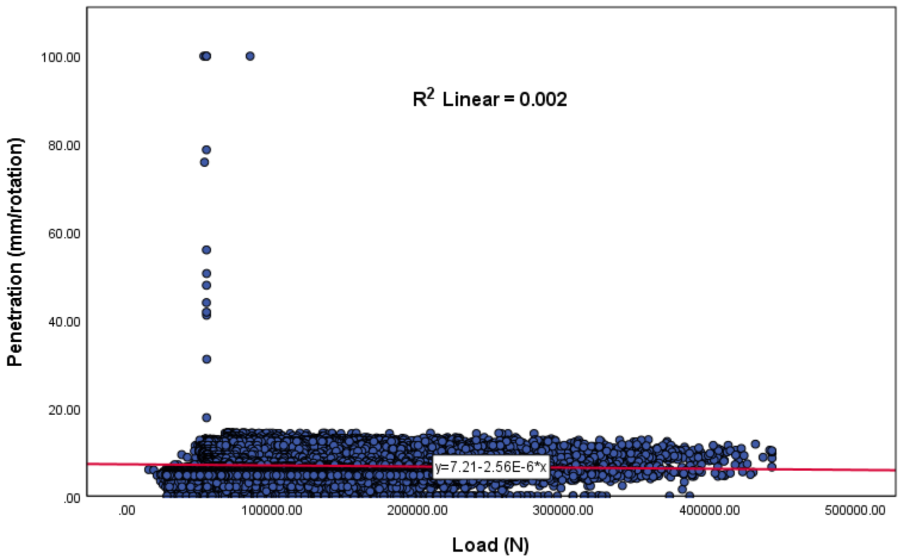


Figure 6-25 Linear Regression analysis between Load (DCLM) and Penetration (TBM) for Track 35

6.3.2 Regression Analysis for Modified Individual Track

As a result of the manual inspection of the main data, it was determined that the load parameter recorded by DCLM continually varies as the TBM progresses while the TBM parameters remain constant for a single cutterhead rotation, changing only when the new rotation begins. Therefore, thanks to the angle data recorded by DCLM, all data was rearranged to have individual cutterhead rotation and corresponding data. However, instead of utilizing different data for every degree of one cutterhead rotation, by calculating the mean value, one load, one thrust force, one advance speed, and one penetration was accepted for each rotation (Table 6-1). Eventually, linear regression analysis was conducted again for each track based on the new input data *Figure 6-26 - Figure 6-27*.

Load (N)	Thrust Force (kN)	Advance Speed (mm/min)	Penetration (mm/rotation)	Cutterhead Rotation
31059.85	24112	5.9	5.6	Rotation 1
59110.73	23478.78	9.698333	9.228605	Rotation 2
52606.62	23794.18	9.220183	8.820183	Rotation 3
62807.58	23685.6	9.084455	8.729818	Rotation 4
48346.51	23442.74	9.299333	8.899333	Rotation 5
47732.12	23386.64	9.545167	9.106458	Rotation 6
33396.12	23507.82	7.172371	5.976976	Rotation 7
29793.29	23615	8.9	7.6	Rotation 8
46499.48	23601.52	9.050556	7.6629167	Rotation 9
45661.65	23598.07	8.924955	7.4777381	Rotation 10

Table 6-1 Final Input data for Linear regression analysis (only 10 row)

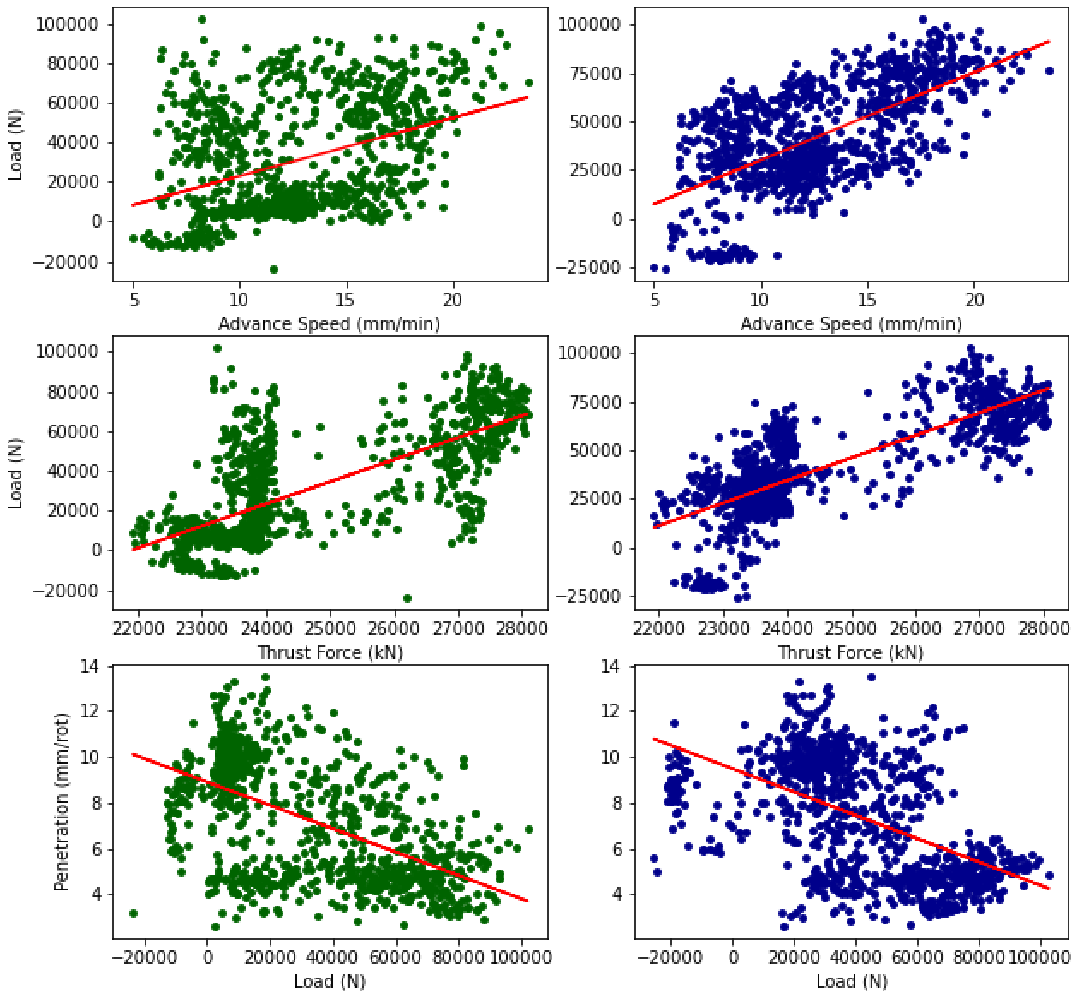


Figure 6-26 Linear Regression analysis between corrected Load (DCLM) and TBM data forTrack 15 (green) and Track 22 (blue)

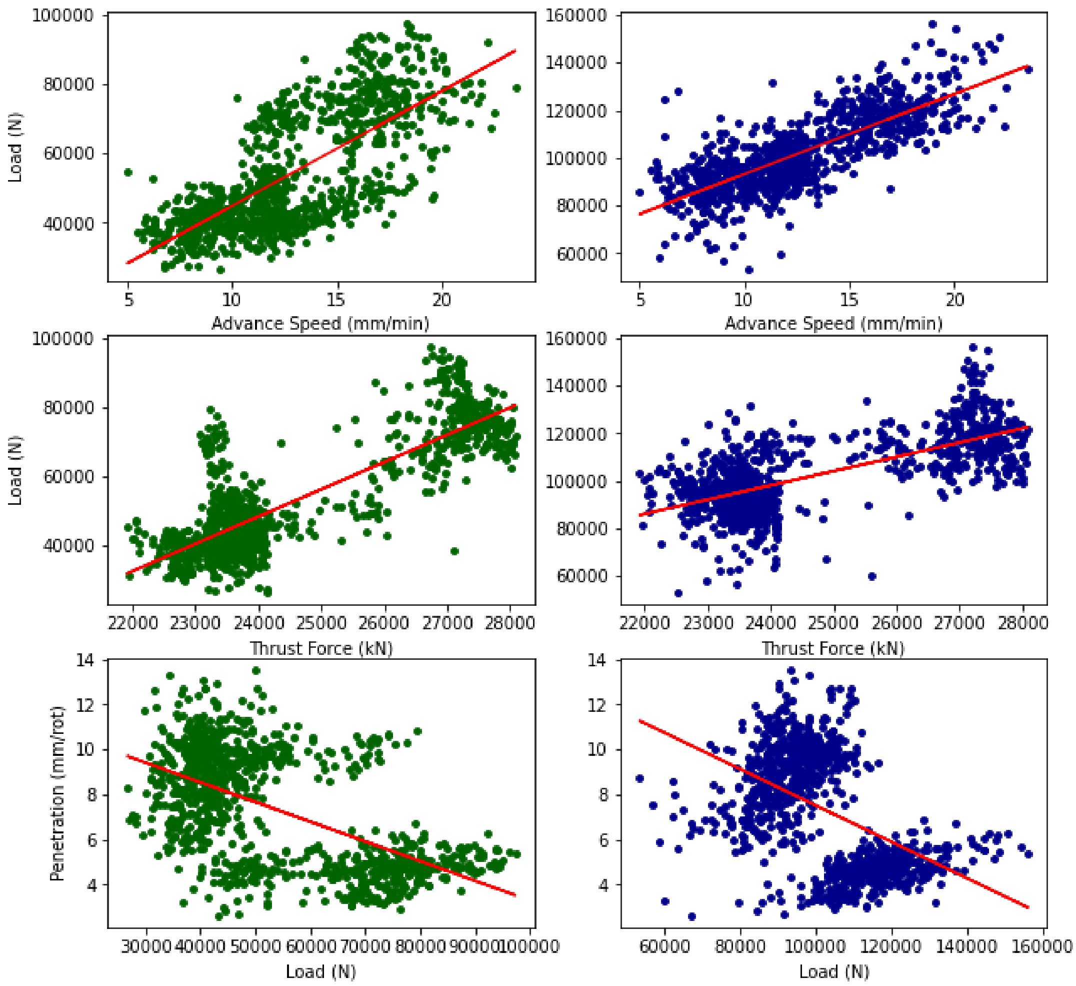


Figure 6-27 Linear Regression analysis between corrected Load (DCLM) and TBM data for Track 28 (left) and Track 35 (right)

6.4 3D Modelling

After achieving an acceptable level of correlation between the DCLM sensor and certain TBM parameters, the next step was to establish the 3D model of DCLM (Figure 6-28, Figure 6-29). Since the data of four DCLM sensors were investigated in the previous stages of the research, the model consisted of 4 rings of different sizes intertwined. The load parameter was used as a colorant in the model in order to visibly see the cutting force exerted by cutting tools at different points in the formation throughout excavation. The color scale specified in Figure 5-5 was reconstructed for the model as well, in order to obtain a more explicit model.

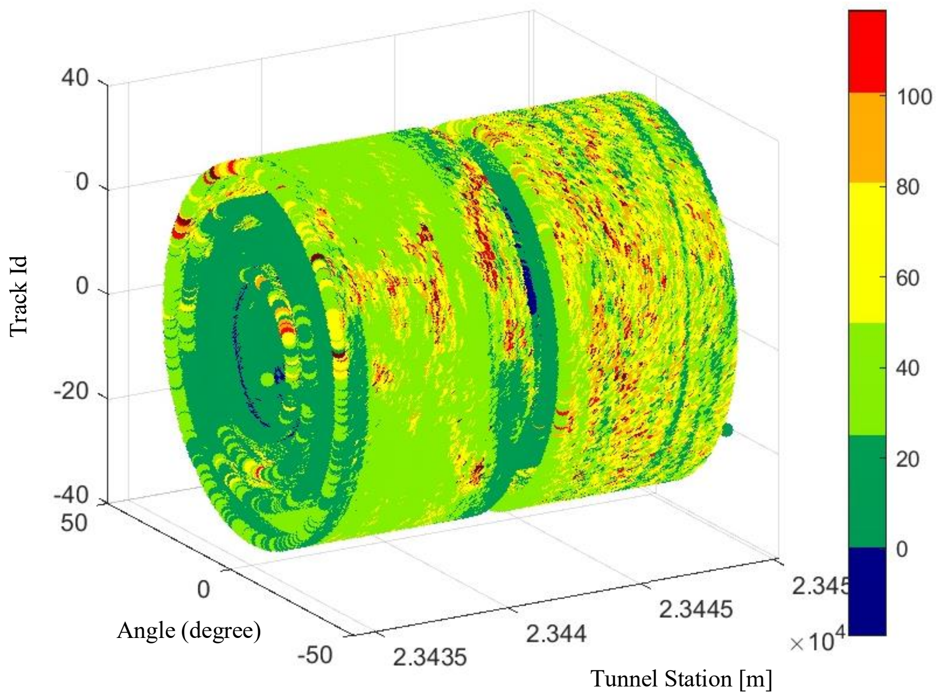


Figure 6-28 3D model of all tracks based on the Chainage (m), Angle (degree), Id(number) and Load(N) ***(1)***

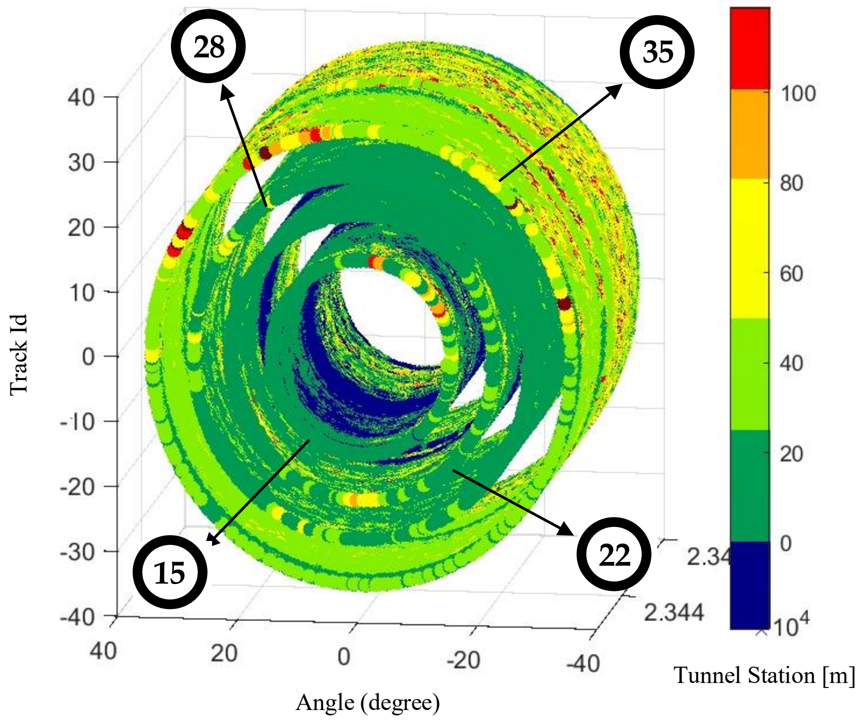


Figure 6-29 3D model of all tracks based on the Chainage (m), Angle (degree), Id(number) and Load(N) ***(2)***

6.5 2D Modelling

The principal objective of 2D modeling was to design a more understandable model because, as it can be noticed from the 3D model, it is challenging enough to understand the formation due to the complexity of color and pattern. Therefore, it was decided to transform a 3D model to 2D (Figure 6-31). Another crucial factor that could influence the correctness of the final geological model was data loss so that the modeling technique chosen had to enable us to use a substantial part of the data. The possible approach to achieve this was to divide a tunnel face into 280 equally sized pieces and find a mean value of load for each piece (Figure 6-30). Thanks to this, it would be possible to determine the load applied to various parts of the excavation face every 10 cm.

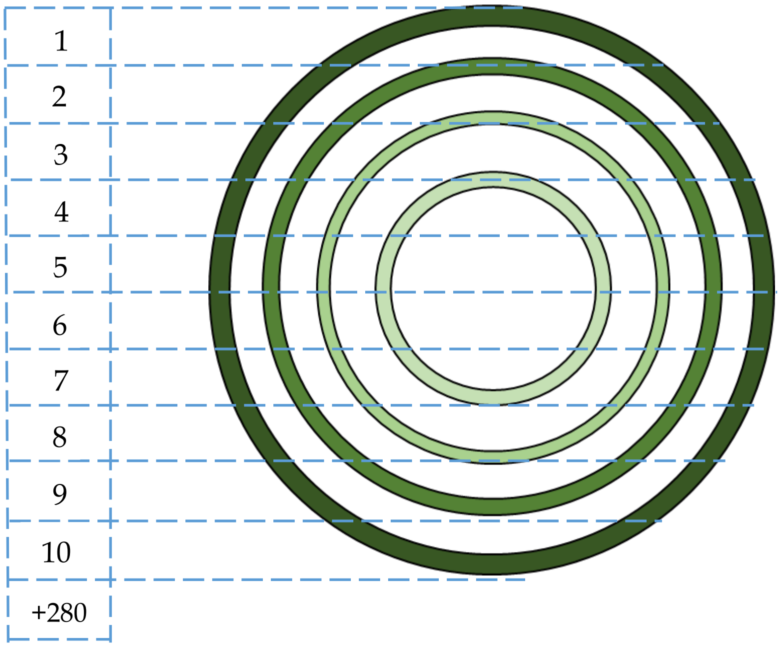


Figure 6-30 Splitting the 3D model of DCLM into equally sized 280 horizontal pieces to obtain data for 2D conversion (front view)

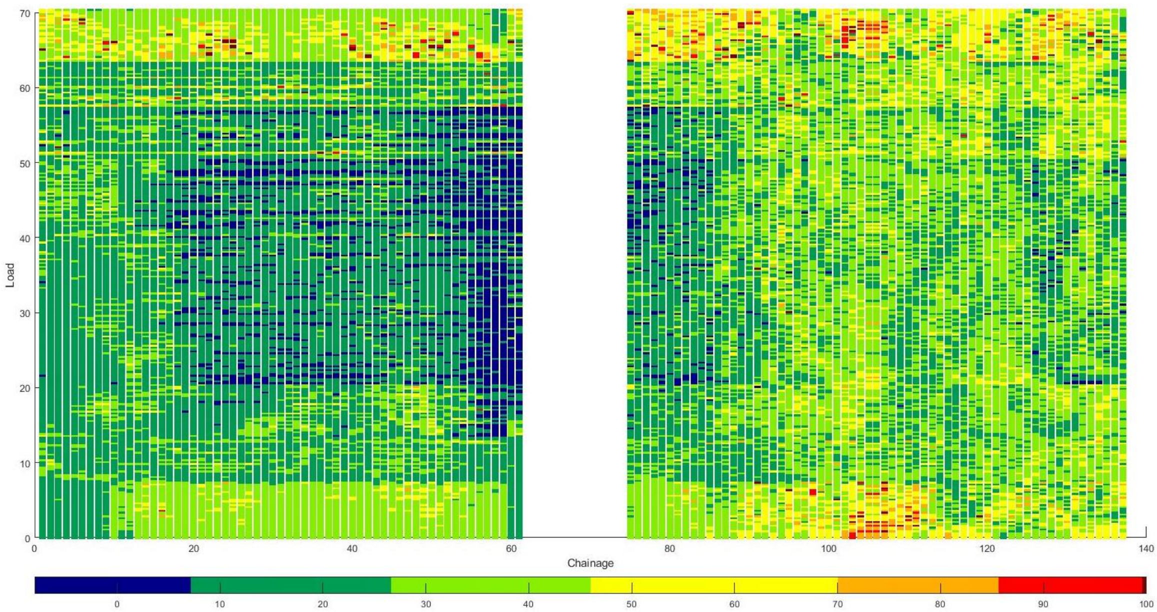


Figure 6-31 Converted DCLM model from 3D to 2D

Chapter 7

7 Discussion of Results

As this was the first research regarding the link between DCLM data and TBM parameters, the main purpose was to prove a certain level of connectivity, rather than strong connection. Therefore, three different scenarios were determined for the R-square which would be obtained from the regression analysis. These scenarios were a) 0.5-0.6 fair b) 0.6-0.7 satisfactory c)> 0.7 Good.

Both visual and statistical correlation analysis showed that DCLM sensors do not affected by Main Drive Speed and Torque, while the Advance Speed and Thrust Force have enough connection with sensors. Besides, since DCLM record all the data thanks to the excavation of the tunnel face by cutting tools, it was highly probable to obtain connection between Load (DCLM), and Penetration data recorded by TBM. However, results illustrated in the Table 7-1 shows that DCLM data is mainly affected by Thrust Force and Advance Speed.

	Parameters	R-square Value
Track 15	Thrust Force- Load	0.505
Track 22	Thrust Force-Load	0.614
Track 28	Thrust Force-Load	0.698
	Advance Speed-Load	0.525
Track 35	Advance Speed-Load	0.619

Table 7-1 Results of final regression analysis for each track

Based on the regression analysis, it was decided that DCLM data can be used to establish a geological model for the advanced distance. However, the final decision can be taken only after the comparison between the 2D DCLM model and the geological cross-section of the completed part of the tunnel. This cross-section has been created by using soil parameters encountered and chainage (Figure 7-1).

As stated in the Project Specification, the ground condition is mixed in the tunnel project, which provides the data used in this research. It is evident that the mixground condition usually is made up of a mixture of different geological formations. These formations also include a tiny proportion of other formations, which cannot be displayed on the geological cross-section.

On the other hand, geological cross-sections are more understandable since they only illustrate the general formation encountered during excavation. In contrast, DCLM sensors are capable of recording forces applied to very small areas. In fact, the reason for the mixed color distribution, which is the main difference between the two figures, is that the load applied to these areas is shown in the model. By considering these two factors, existing geology and sensitivity of sensors, we could say that data obtained from DCLM can be used to establish a geological model in more smooth geologies or, in other words, where there will only sharp changes between different formations, such as hard rock. However, this idea requires additional research.

Another point to note is that the input data may not be 100 percent correct due to technical errors. Currently, there is no technology to check the accuracy of DCLM data or to sift load data applied to small areas from the master data. This process can be done manually but will take a lot of time. According to Herrenknecht engineers, such technology can only be developed within the next 2-3 years.

In addition, according to engineers' site reports, before reaching the 23435 (m) – 23450 (m), some electric cable problems occurred in the DCLM system. Although it was fixed in a short time, certain errors can arise in the main data due to this event.

In a nutshell, according to the author, there is a possibility to have both higher correlation values and a more accurate geological model in smooth geological conditions.

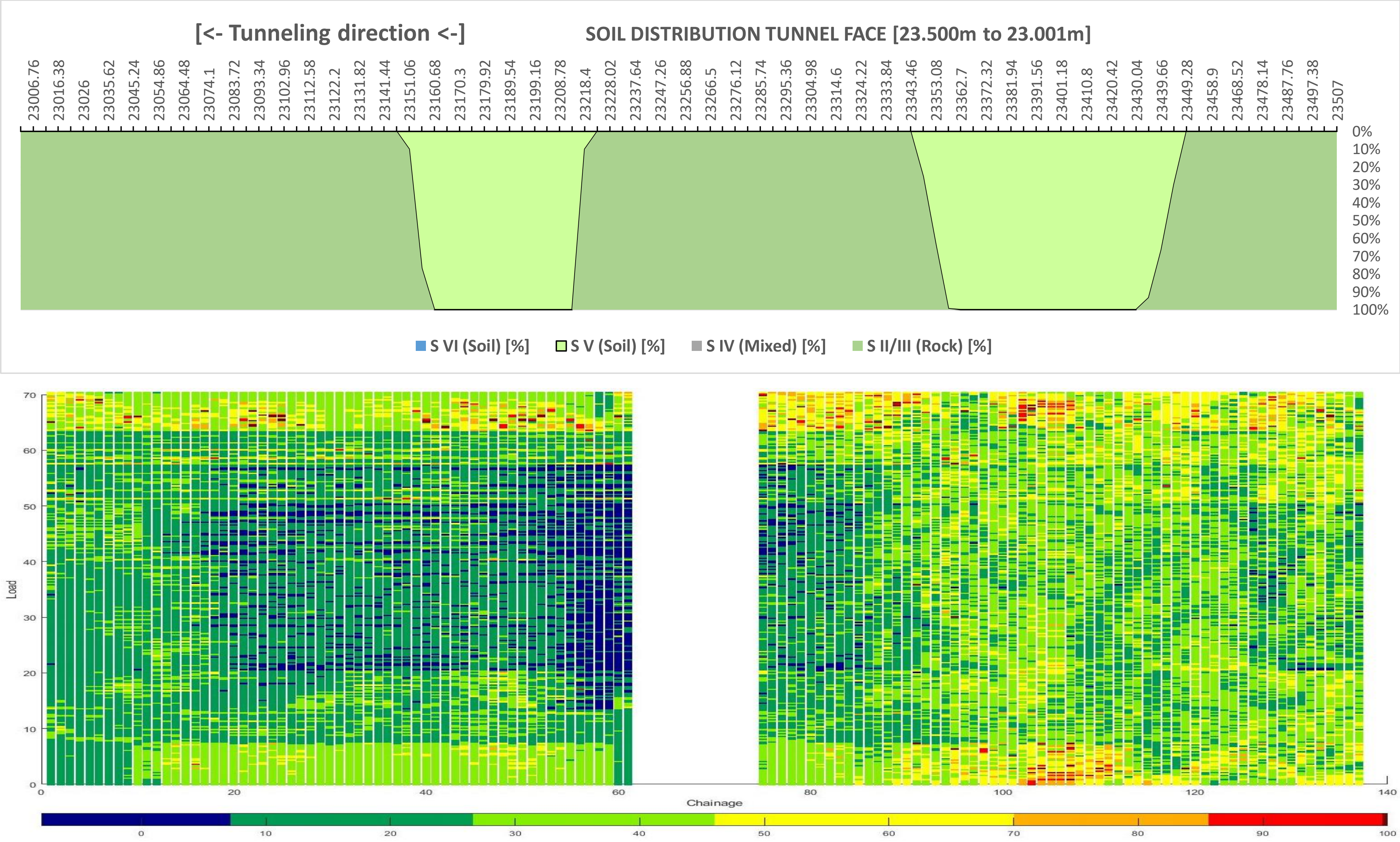


Figure 7-1 Comparison between geological cross-section and 2D DCLM mo

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