GERMAN - MONGOLIAN INSTITUTE FOR RESOURCES AND TECHNOLOGY

Baganuur Coal Mine LC

Reducing of vibration influence on auger drilling rig (SBR-160A-24)

Bachelor thesis

by

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Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

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independently and without undue external help. I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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Abstract

The main objective of this work is to analyze the vibration, to find the sources and to examine for optimal solutions in SBR-160A-24 auger drilling rig. Design and modelling are based on result of this research work.

Auger drilling rigs used in 'Baganuur LC' coal mine. The company spends half of its expenses of operations costs on auger drill bits. There are a number of reasons such as rotational speed of drill is a constant for drilling different hardness material in layers. Currently, they do not have any monitoring and automatic control system to manage the current of motor and the rotational speed. The machine can work under high vibration itself and a monitoring system with smart sensors are not suitable for under high vibrations. The experimental result was proved the auger drill rigs had a high vibration. Thus, it leads to the bachelor thesis is researched vibration causes and their influence. From the measurement results, the vibration reducing solution founded and there some calculation and analysis of modelling done as needed.

Acknowledgement

First of all, I would like to thank GMIT family (all my professors, lecturers, students and whole staff) for giving me the opportunity to gain my knowledge and skills during my study years at the GMIT. The completion of this undertaking would not be possible without their supports, suggestions and recommendations. As well as, a team of 'Baganuur LC' coal mine for sharing experience and helping with supplementary materials. Their contributions are sincerely appreciated and acknowledged.

I am grateful to my supervisors Professor Ph.D. Ariunbolor and M.Sc. Baljinnyam for their guidance, support and patience in helping complete this thesis. I thanked particularly to their helpful comments and valuable guidance during the study and development of this research.

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List of Abbreviations:

GMIT	German-Mongolian Institute for Resources and Technology
CFA	Drilling with Continuous Flight Auger
LC	Limited Company
SI	The International System of Units
TPP	Thermal Power Plant
WOB	Weight on Bit
3D	Three Dimensional

Auger	Drilling device, or drill bit, that usually includes a rotating helical screw blade
Drilling rigs	A machine that creates holes in the earth sub-surface
Inclination	The angle at which a straight line or plane is inclined to another
Vibration	Vibration can be defined as simply the cyclic or oscillating motion of a machine or machine component from its position of rest.
WOB	Weight on bit is the amount of downward force exerted on the drill bit.
Track	A continuous articulated metal band around the wheels of a heavy vehicle such as a tank, intended to facilitate movement over rough or soft ground.
DeweSoftX2	This program is the most advanced data acquisition, recording and analysis software.

List of Symbols:

f	The coefficient of strength on the scale of Professor M.M.Protodyakonova
F	Force
d	Diameter of drill
$\tau_{workpiece}$	Shear strength of workpiece
$\sigma_{workpiece}$	Tensile strength of workpiece
k	The spring stiffness
w	Frequency of vibration
w_n	Natural frequency
ξ	Damping ratio
F_t	Total (maximum) thrust force (N)
F_f	Friction force (N)
F_g	Force of gravity (N)
α	Angle of inclination
μ_s	Coefficient of sliding friction
m	Mass (kg)
g	Acceleration due to gravity (9810 mm/sec^2)
V	Velocity (mm/sec)
T_a	Acceleration time (sec)
D	Move distance (mm)
t	Move time (sec)
a	Acceleration (mm/sec^2)
τ	Input torque (Nm)
η_s	Screw efficiency
η_b	Timing belt efficiency
ω	Angular speed (rad/sec)
P_{out}	Output power of the motor (kW)

Chapter 1

1.1. Overview

1.1.1. The company

The Baganuur LC coal mine is located 130 km to the east from Ulaanbaatar. The coal deposit is 12 km in length from the northeast to the southwest and covers 4-5 km in width (Figure 1.1). The coal deposit consists of three main coal seams and the compound of coal based B2 grade coal for to use in energy production. The total reserves of the deposit were determined by exploration in 1977.

Specifications	Units (SI)	Amount
The area of mine site	ha	3,164.4
Resources of coal deposit (On January 1, 2015)	ton	812,000,000
Dimensions of mine (L x W)	km	12 x 4
Number of seams		3
Inclination of layers	degrees	8-20
Average depths of soil	m	80
Ash content of coal	%	12-17
Moisture of coal	%	28-33
Sulfur content of coal	%	0.3-0.5
Calorific value	Kcal/kg	3200-3600
Coal weight	ton/m^3	1.23-1.31
Soil weight	ton/m^3	1.95-2.25
Flow of groundwater	m^3/h	1100

Table 1 - The main specification of Baganuur LC coal mine

Baganuur LC established in 1978 for the purpose of supplying coal for Thermal power plants, which are located in the Central Energy System. In 1995 company privatized when to become by state dominating owned Baganuur LC. 75% of the shares are owned by the state and 25% are owned by citizens. On February 9, 2015, it produced 100 million tons of coal.

Figure 1. 1 – Baganuur LC coal mine

The annual production capacity is 4.0 million tons, and is produced to be 3.6-3.8 million tons of coal depending on the domestic demand of coal and removed 16.0 to 18.0 million cubic meters of soil. The mine is supplied 60% of Mongolia's coal demand and provided 70% of Central Energy System (Thermal power plants Table 1.2). 0-200 mm size of coal is transported by wagons and other vehicles.

Thermal Power Plants		Annual supply	
		(thous.tn)	Shares to total consumption (%)
1	TPP-4	1600	60
2	TPP-3	1100	100
3	TPP-2	210	100
4	Darkhan TPP	250	60
5	Erdenet TPP	120	50

Table 2 - The main consumers

1.1.2. Handout of auger drilling rigs

Baganuur LC is using lot of machines and equipment for operation. For example, those kinds of machines are auger drilling rigs, hydraulic excavator, dozer, wheel loader, rope shovel, dragline, small truck and dump truck. Auger drilling machines are done with a helical screw with auger drill bit which is driven into the ground with rotation, the earth is lifted up the borehole by the blade of the screw and the auger drill bit. The company have six auger drill rigs (SBR-160A-24). From that nowadays four auger drilling rigs are working on site, additional one is not working (but it can work when other four machines are a break down) and another one is updating (equipped with extra components and devices).

The SBR-160A-24 machine is designed for drilling vertical and inclined wells with a cutting-edge crown wheel for coal and rock with a coefficient of strength f up to 6 on the scale of Professor M.M. Protodyakonova for the extraction of minerals by the open method. (Appendix A - “Table 1.4”)

Technical capacity, m/h, not less than for	
rock strength $f = 1 - 3$	80
$f = 3 - 6$	54
Nominal diameter of borehole, (mm)	160
Vertical drilling depth of borehole, (m)	Up to 24
The angle of inclination of the borehole to the vertical, (degrees)	0; 15; 30
The upper limit of the rotation frequency of the drill, (rpm)	3.33 (200)
Upper limit of feed force, (kN) not less	80
Travel speed, km / h	0.9
Gradeability, (degrees)	15
Feed speed in operation, (m/min)	0…3,2
Weight, (kg)	28000
Overall dimensions of the machine, (mm), not more than the working position	
Length	7495
Width	4900
Height	12980
Overall dimensions of the machine, (mm), not more than the transport position	
Length	12640
Width	4800
Height	4685

Table 3 - Technical specifications of SBR-160A-24

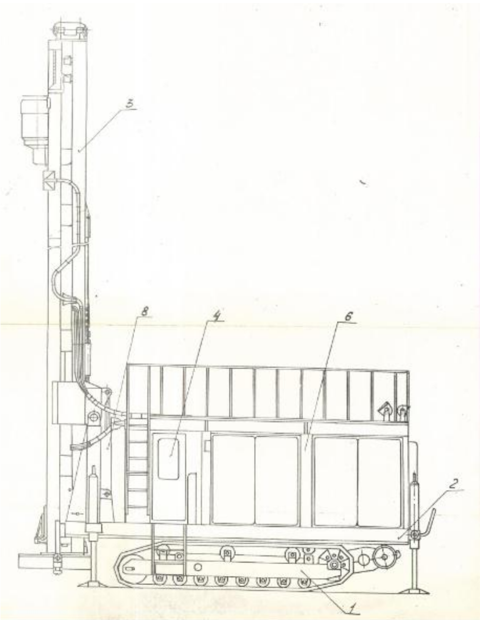


Figure 1. 2 - Scheme of SBR-160A-24

Figure 1. 3 - SBR-160A-24

From scheme of SBR-160A-24:

1 - Tracked drive, 2 - Frame, 3 - Drilling part, 4 - Cabin, 6 - Body, 8 - Screw piles auger lift cylinder

1.1.3. Drilling process

Why should the coal mine use auger drilling rigs? The reason is excavator cannot excavate in a some of the layers. For example, the coal mine of Baganuur layer formation consists of sandstone with thin layers of siltstone with a rock coefficient of strength f from 6 to 10 on the scale of Professor M.M. Protodyakonova (Appendix A - “Table 1.4”). Then they use auger drilling rigs which are to prepare wells of explosive materials (like a bomb). After that wells are exploded by bomb. And it is to become ready to excavate the layers using the excavator.

Generally, there has many kinds of methods for borehole drilling. For instance, Kelly drilling, continuous flight auger drilling, full displacement drilling, double rotary drilling, drilling with hammer grab, reverse circulation air injection drilling and down-the-hole drilling (1). But auger drilling rigs (SBR-160A-24) is to belong to the category of continuous flight auger drilling (CFA). CFA is belonging to the dry rotary drilling methods. It is proper for predrilling also for the installation of cast in place piles. The soil (under certain conditions also rock) which is loosened at the auger tip is carried to the surface by the auger flight.

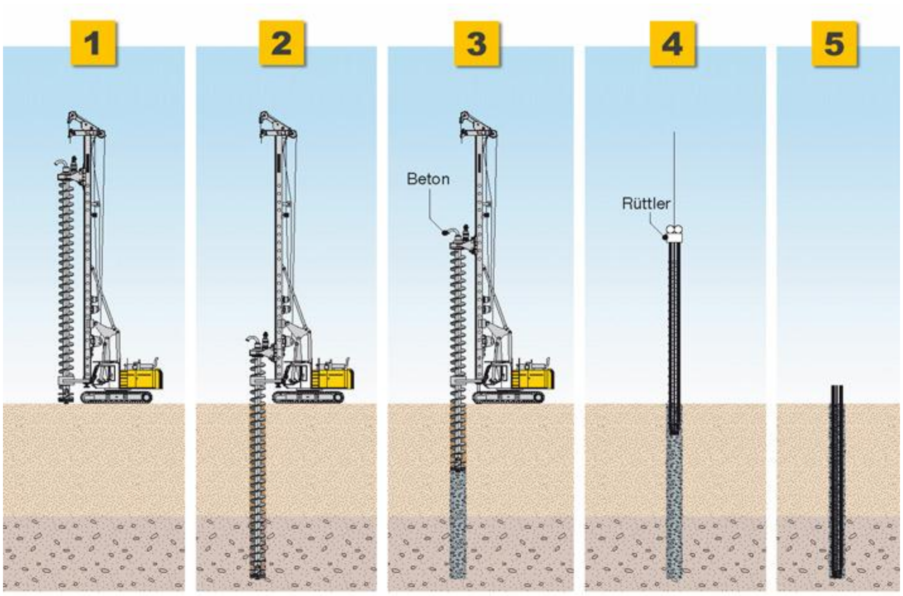


Figure 1. 4 - CFA drilling process

Figure 1.4 shows procedure of producing a cast-in-place concrete pile with continuous flight auger drilling: (almost same technique to prepare wells of explosive materials)

1. Positioning at the drilling point
2. Auger drilling until the final depth is reached
3. Extracting the auger and pumping in concrete
4. Pressing or vibrating in the reinforcement
5. Finished pile

1.2. Problem statement

Initially, the company was founded by Russian investment, then most of its equipment are Russian's outdated technologies. But due to long-term operations, equipment has deteriorated and some of them outed of services. In some cases, the component of the deteriorated equipment has replaced other parts by Mongolian engineers. It leads to change the duty of machines, to lose working functions and operation controls. In some cases, the component of the deteriorated equipment has replaced other parts by Mongolian engineers. It leads to change the duty of machines, to lose working functions and operation controls. As well as, those kinds of problems are heading to affect normal working components. On the other hand, it is increased operation and maintenance cost. The auger drill rigs (SBR-160A-24) are one of the best an example. Those machines are done with a helical screw with auger drill bit which is driven into the ground with rotation, the earth is lifted up the borehole by the blade of the screw and the auger drill bit. The coal mine spends half of its expenses of operations costs on auger drill bits. This is because the current of a

Figure 1. 5 – Borehole drilling (SBR-160A-24)

Figure 1. 6 – Auger drilling bit

drilling rig electric motor is more than the normal or adjusted current. Therefore, one auger drilling bit (Figure 1.6) is done in one day. Auger drilling rigs used in Baganuur coal mine do not have yet any monitoring and automatic control system for electric motor current for operating the drilling rigs. Thus, a monitoring system with smart sensors needs to developed.

A monitoring system with smart sensors are not suitable for under high vibrations. Because, smart sensors are very sensitive then they could give a wrong and false data. Furthermore, a high vibration is to damage on monitoring system. those kinds of devices are too much expensive and to require high capital cost for installation.

Because of that, this bachelor work is intended to reduce vibration influence problem on above mentioned.

1.3. Research objectives

This research aim is to reduce vibration influence on a drilling machine. Also, to measure the vibration frequency, to analyze the data and to identify suitable range of vibration frequency and amplitude for properly working conditions of monitoring system.

The objectives of this bachelor thesis are as follows:

- ⇒ To study about a structure of machine and to find sources of vibration from an important component.
- ⇒ To research and to read articles about the vibration of specific machine parts and to find the reasons of causing vibration and effects of vibration.
- ⇒ Utilization of some specific conditions existing in the directional/vertical drilling process in order to minimize the vibration.

1.4. Structure of the thesis

The thesis is structured in four chapters and includes a general conclusion, a list of references and two appendices. The study is organized as follows.

Chapter 1 gives brief overview of the Baganuur LC coal mine and covers research objectives and problem statement. Additionally, this chapter provides short information of auger drilling machine (SBR-160A-24) and drilling process.

Chapter 2 begins with introduction of thesis and will review vibrations of drilling machine literature.

Chapter 3 will review description of auger drilling rig (SBR-160A-24) and common issues of important parts that could cause in vibration. The chapter continues with the fundamental explanation methods of experiment and characteristic of vibration measurement equipment.

Chapter 4 will present about data collection and their analysis of the vibration measurement. Then result section will explain and introduce of the vibration reducing device. The following chapter will continue with discussions.

Chapter 5 concludes the research work and provides recommendations for future development of the suggested techniques.

Appendix A will display additional tables, figures and supplementary material.

Appendix B provides additional information which are consist of some definitions.

Chapter 2

2.1. Introduction

Mongolia has plentiful supplies of many types of natural resources and a one of them is coal. It has approximately 100 billion tons of coal underground. Consequently, the mining industry and companies has been expanding in Mongolia. Insomuch that so many techniques, technologies and equipment are needed and used. There are many problems of technical, software and environment to cause with this. For instance, the high vibration of auger drilling rigs is biggest problem for to design, implementation and testing of monitoring system with smart sensors for electric motors of drilling rigs.

Auger drilling rigs (SBR-160A-24) are usually used in “Baganuur LC coal mine”. The coal mine spends half of its expenses of operations costs on auger drill bits. Therefore, one auger drilling bit is done in one day. Thus, a monitoring system with smart sensors needs to developed. The main aim of this bachelor thesis is to reduce vibration influence on a drilling machine. The reason is those kinds of machines to work under the high vibration especially when transporting (to change the locations for drilling) and drilling the borehole.

2.2. Literature review

This section will review vibrations of drilling machine literature. In simplest terms, vibration has in motorized equipment. Those kinds of mechanical systems make up drive motors, driven devices (pumps, gearboxes, turbines, compressors and etc.) and the belts, bearings, gears, shafts, and other elements. Most industrial machines are engineered to operate smoothly and avoid vibration, not produce it. These kinds of machines, high vibration can define problems or deterioration in the equipment. But machines vibration range is different from each other for that applications and working conditions. The undesired higher vibration itself can create trouble condition for equipment. Vibration can result from a number of conditions, acting alone or in combination. Keep in mind that vibration problems may be caused by auxiliary equipment, not just the primary equipment. These are some of the major causes of vibration (2). The below reasons are a very general condition.

- **Imbalance:** Unbalance of rotating component will cause vibration when the center of gravity is not exactly in center line (3). Imbalance can be caused by machining error (manufacturing defects) and service issue (maintenance). While rotating speed of machine increases, the influence of imbalance grows larger. That means undue vibration could cause in the equipment. Obviously, it can damage bearing system as well as the effect on other sensitive parts.
- **Misalignment/shaft runout:** The perfect alignment is very important when axes (main shafts) of two rotating objects are connected. Typical alignment errors are three types which are parallel misalignment, angular misalignment and combined parallel-angular misalignment (Appendix B). Misalignment may be produced by long term function or under high loading condition (thermal expansion) and unfitting reassembly after maintenance.
- **Wear:** In rotating machinery has two main types of bearings: ball or roller bearings and sleeve bearings. When a ball and roller bearing race becomes joined, for instance, the bearing ball and rollers will produce a vibration each time they going through in over the damaged area. Additionally, if a gear tooth damaged thickly chipped or drive belt that is wear down, that can also produce vibration.
- **Looseness:** Looseness can give a chance any vibration presents to cause damage, such as bearing wear, drive belt wears down and other components.

As mentioned before, these four reasons are a very common thing for causing vibration. But the purpose of the review was to gather relevant information about:

- ✓ Vibration sources in electric motor
- ✓ Vibrations of during the drilling process
- ✓ Tracked vehicle vibration response considering the track circuit vibration

2.2.1. Vibration sources in electric motor

Vibration problems can happen at any moment in the operation of an electric motor and even assembly parts or installation process. While vibration problem would suddenly occur, it is most important that reacts immediately to solve the problem. If not solved as quickly, that could face as a long-term damage to the motor or directly failure problem. As a result of problem, machines and plant would break down which lead in directly loss of production or increase a maintenance cost. William R. Finley (4) reviewed the several kinds of sources of electrical and mechanical forces will be described. These two forces are to cause vibration of motor. The correlations between the stator and rotor can cause many different forces which are electrical causes (Figure 2.1).

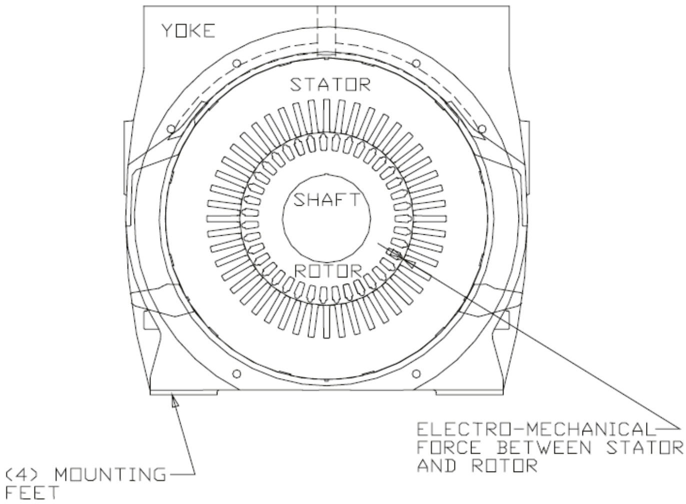


Figure 2. 1 – Rotor and Stator of Electric motor

There have two kinds of peak forces during each cycle of the voltage. For example, on a 2-pole motor has "Flux - Flux around a stator" and "Force - Force between a stator & rotor" (Figure 2.2). In Katalin Agoston's (5) article considered flux variation around the state which produces a variation of attractive force between the stator and rotor. This force is called electromagnetic force. When the current of stator is at maximum or at minimum, electromagnetic force has maximum amplitude. Hence the force will take second frequency of the power sources (twice line frequency vibration) (4)(5).

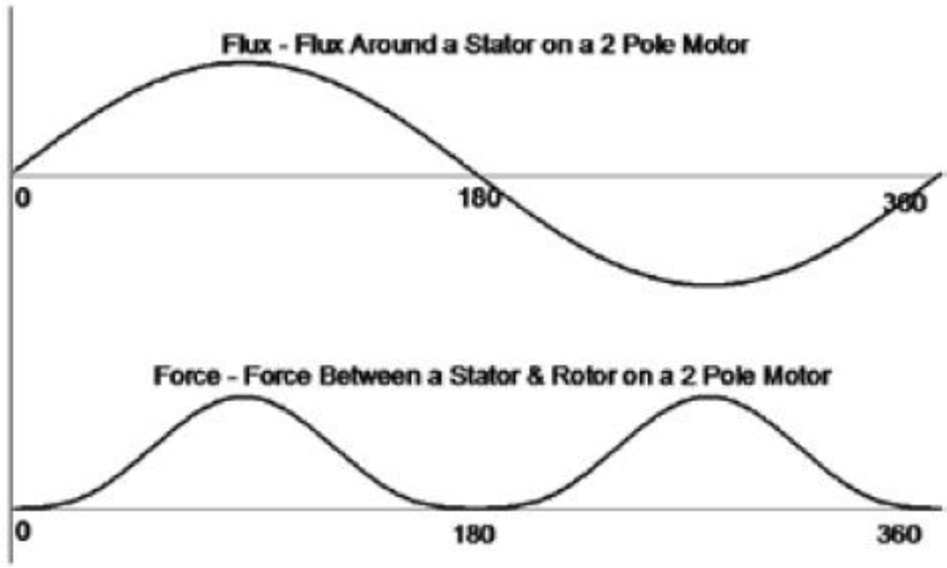


Figure 2. 2 - One Period Flux Wave & Magnetic Force Wave

This special vibration is very sensitive to the motor's base stiffness, feet and frame and to the evenly how assessment of air gap between the stator and rotor. As well as, that is affected by dissymmetry of the rotor. One more reason can be damaged rotor bar or short circuit of a segment of the winding. If broken rotor bar exists in the rotor then the current cannot exist anymore. As a consequence of this, magnetic field will also no exist in around the rotor. On the other side, a broken rotor bar could cause resistance between the case and rotor. In this condition, this is producing heat during the full load in motor. That is cause thermal expansion of main shafts which means to create misalignment/shaft runout in the rotor.

As well as, mechanical causes (1) can be major reasons of vibration as mentioned above, for example motor unbalance, unfit base and usage of the bearing. One of the pretty well-balanced equipment is obviously electrical motor. The unbalance condition is easy caused by such as the cooling fan for dirt build up, or broken fan blades. Also, the coupling hub is another kind of reason (6). The eccentric bore and improper key stock length [in Equation 1] are the most things of the coupling hub can lead to unbalance.

In Figure 2.3 is shown the coupling hub. There are a handful of methods to determine proper key stock length, but the easiest is:

Hub length + Key slot length ÷ 2 = Length of key stock [1]

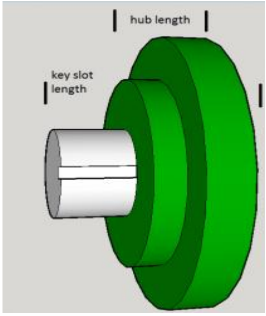


Figure 2. 3 – The Coupling hub

Mainly, in unbalanced rotating equipment will create all forces on its bearings and transmit them throughout its structure and into the foundations. That means bearings is easily damaged more than anything. Especially, inner race, outer race, bearing cage and roller spin of bearings are weakened by that forces. The Figure 2.4 will provide examples of general problems of unbalanced motor. Unbalance is one of the significant problems confronted in the electric motors.

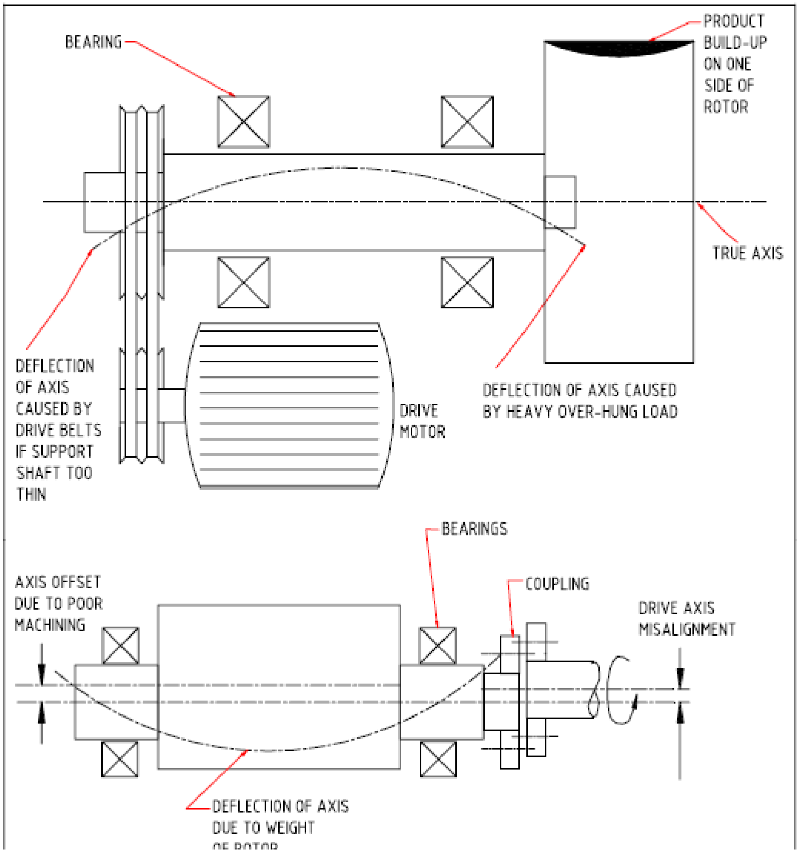


Figure 2. 4 – The unbalance of Motor Axis (7)

Morgan W. (4) research stated the vibration specificities of an induction motor have been examined experimentally and using the finite-element modelling. His experiment based on modal testing methods then results was corresponding to each peak in the sound power spectra, a vibration mode can be found very close to it (Figure 2.5). The purpose of experiment is to consider the effect of end shields on the vibration modes.

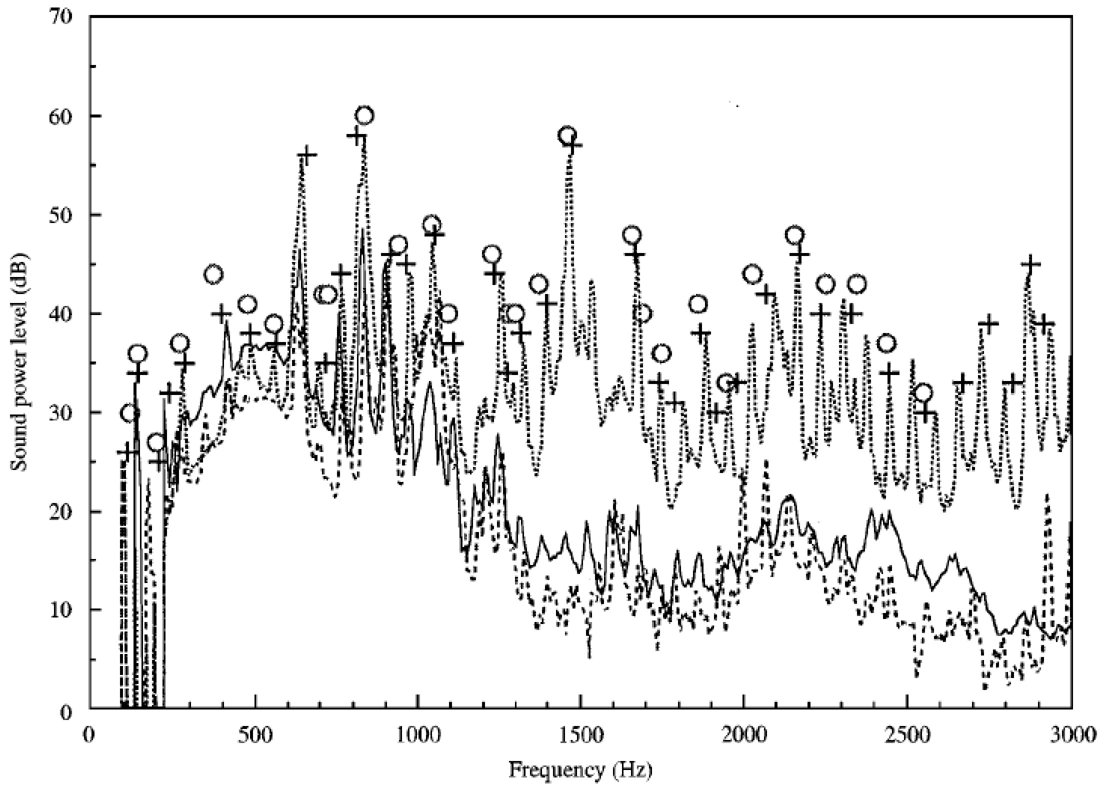


Figure 2. 5 - Sound power spectra and modal testing results of the motor: ——— Benchmark, ···· inverter 1, - - - - inverter 2, + Modal testing state 1, o Modal testing state 2

Up till now many researches on the electric motor about vibration and sound frequency characteristics have been published. Holopainen T. (8) studied rotor vibrations of electric motor. He did the linearized simulation model (Figure 2.6) during the effects of electromechanical interaction in rotor vibrations of electric motor. The complete and linearized simulation models gave mostly similar responses. The simulation results show the higher frequency parts, according to the mechanical vibrations dominate in the

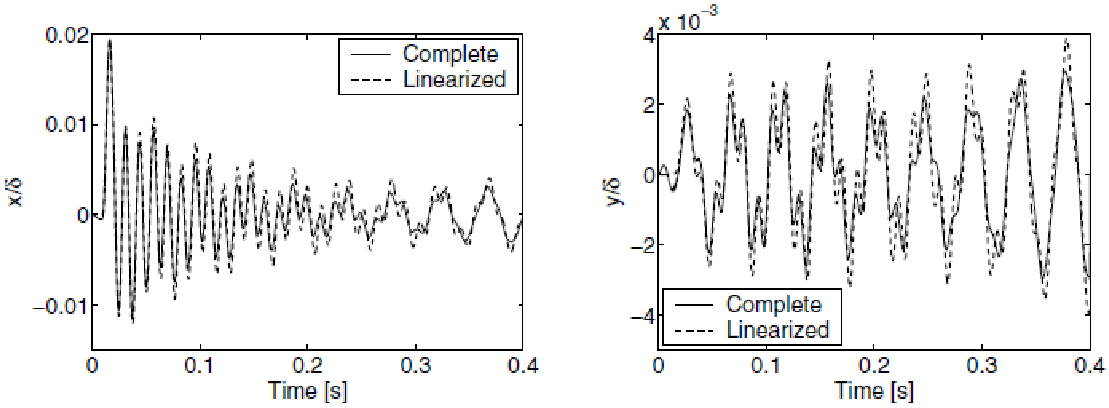


Figure 2. 6 – The horizontal (on the left) and vertical (on the right) displacement response obtained by the complete and linearized simulation models.

beginning of the horizontal response. He stated these mechanical vibrations caused by electromagnetic force which is produced between the rotor and stator.

William R. Finley (9) stated vibration measurements should be acquired with the motor operating under the following conditions:

- Loaded, Coupled, Full Voltage, All Conditions Stabilized (i.e. normal operating conditions)
- Unloaded, Coupled, Full Voltage
- Unloaded, Uncoupled, Full Voltage
- Unloaded, Uncoupled, Reduced Voltage (25% if possible)
- Unloaded, Uncoupled, Coast Down

He observed vibration change during the motor power is cut will provide as same data to reduced voltage operation (Figure 2.7).

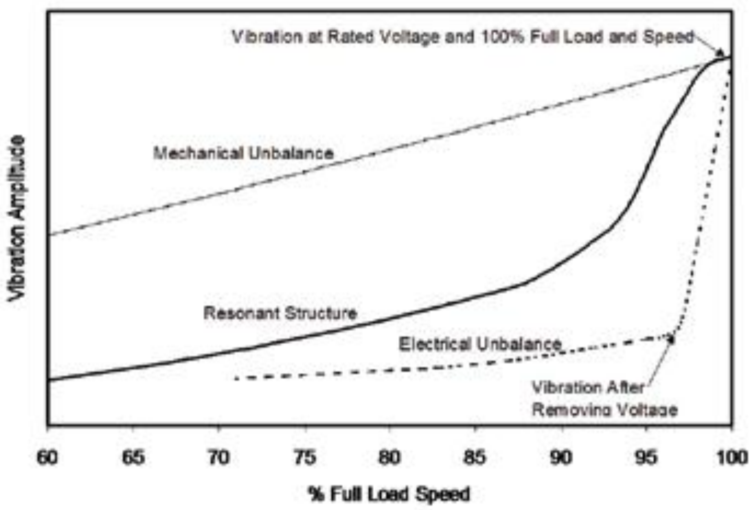


Figure 2. 7 - Vibration after power is cut

Electric motor vibration caused by any reasons such as bearing, motor feet, motor housing, misalignment of the shaft and unbalance of motor. It could be ascertaining the impact of increased vibration on motor reliability.

2.2.2. Vibrations of during the drilling process

Vibration plays an important role for drilling process. There have two sides, the reason is if suitable vibration with in rotational speed helps to loose soil. Definitely, which is a good side (one of the advantages). On the other hand, there has a bad side (disadvantages of drilling) which disturb the drilling operation. Commonly, drilling operation two species of vibrations are identified (10):

A) External Vibrations

If the drilling machine has malfunction which can develop vibration. Then it will affect on spindle of drill during drilling process. Sources of external vibrations are as follows:

- Shaft Misalignment in spindle, motor, nut-bolts and transmitting elements viz., pulley or gear drives
- Improper Foundation of machine
- Loosen fasteners such as nut-bolts, clamps etc.

In generally, external vibrations are studied in Section 2.2.2. which is reviewed from vibrations of electric motor.

B) Internal Vibrations

Internal source of vibration is drilling process itself. In this case, vibration occur due to internal characteristics of the system. From example, these are as follows:

- Spindle speed (Rotational speed of drill)
- Force exerted by workpiece in opposite direction to the drill motion
- Resistive torque by induced by workpiece during material cutting
- High feed rate
- High overhung of drill

Vibrations are generated in the two ways during the drilling process (Figure 2.8):

1. When the machine is taking a position for drilling on the layer and the drill is rotating but machine has not started to drill the layer
2. When the drill is rotating and drilling a hole into the layer

Vibrations of borehole drilling process can be classified into three types (11) (Figure 2.9):

~ Forced torsional vibrations (Figure 2.9 - B)

When the machine is taking a position for drilling on the layer and the drill is rotating. In the present case, when the machine is taking a position for drilling there has not any resistive force in torsional direction. Therefore, vibrations are a very low produced it can

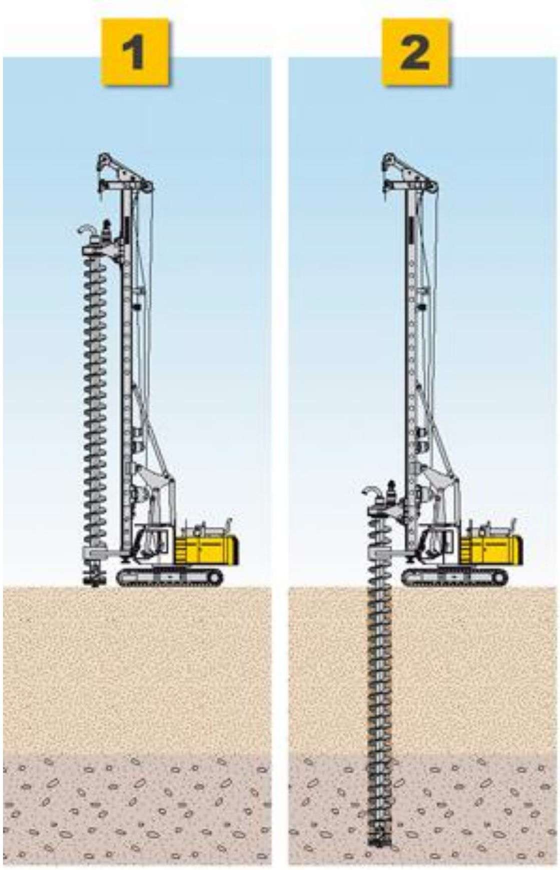


Figure 2. 8 - Drilling process
[1] Machine has not started to drill the layer.
[2] Machine has started to drill the layer.

be neglected (10). When the drill is rotating and drilling a hole into the layer. Certainly, machine will begin cutting the material of hole, torsional shear failure of the material takes place. Force applied on the drill material during torsional failure of the work piece material can be estimated as below:

$$F = \frac{\pi}{16} * d^3 * \tau_{workpiece} \quad [2]$$

Torsional vibrations are produced hence of the rotational movement of drill. Those vibrations produce resistive twisting moment on the drill. If the frequency of vibrations will take a higher value which would crack the drill and drill bit.

~ Forced transverse vibrations (Figure 2.9 - A)

When the machine is taking a position for drilling on the layer, during this time, on the drill has not applied any external force except the force of vibration created by the motor torque (10). As well as, there is resistive force acting on the drill bit in the direction of the transverse vibration of the drill. Therefore, those vibrations can be neglected. However, during the drill is rotating and drilling a hole into the layer the force is produced by the cutting material on the drill bit in the direction of the transverse motion of the drill.

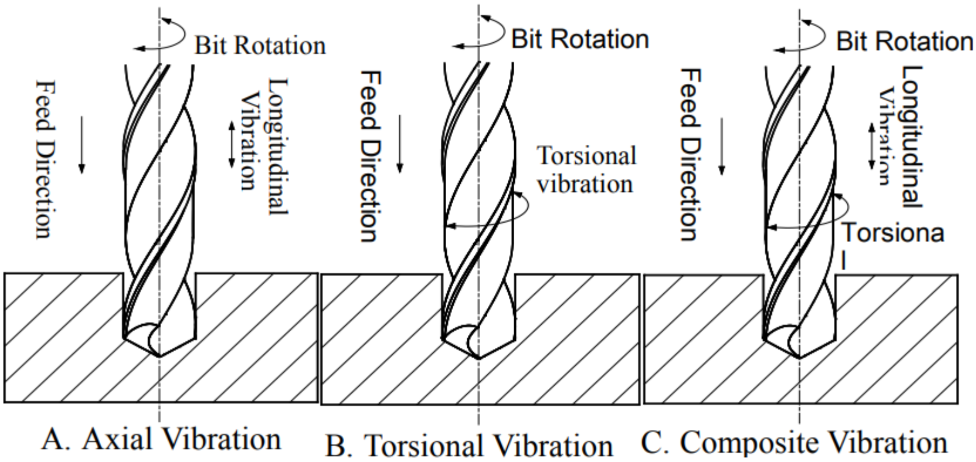


Figure 2. 9 - Vibrations of borehole drilling process

For instance, force is acted in the direction perpendicular to the axis of the drill by cutting material. It can be calculated by using following formula:

$$F = \sigma_{workpiece} * \frac{\pi}{4} * d^2 \quad [3]$$

Now the amplitude of the transverse forced vibration when the drill is drilling a hole into the layer can be calculated by using the following formula:

$$A = \frac{\frac{F}{k}}{\sqrt{(1-(\frac{w}{w_n})^2)^2+(2\xi\frac{w}{w_n})^2}} \quad [4]$$

~ Forced longitudinal vibrations (Figure 2.9 - C)

Forced longitudinal vibrations do not occur when the machine is taking a position for drilling on the layer. Which means no force acts on the drill in the vertical direction during the machine is moving. In that case, also the vibrations can be neglected (10). But then, while machine has started to drill the layer then vertical force is acted on the drill. Because it starts cutting the material to produce the borehole then the tensile stress of material is created by that. In other words, when the material cracks at the time drilling the hole, the longitudinal direction can be reflected as the compressive failure.

The force is acted in the upward longitudinal direction to the axis of the drill by cutting material which can be calculated by using following formula (Equation [3]). As well as, the amplitude of the forced longitudinal vibration can be estimated using the formula given (Equation [4]). These longitudinal vibrations nevertheless, does not impact on the diameter of the hole drilled.

Research article (11) reviewed to find best conditions for steady drilling and as is shown in (Figure 2.10), diagram of the best area for borehole vibrations.

In Figure 2.10, the vertical axis is shown Weight on Bit (WOB) and the horizontal axis is shown drilling speed (Rotational speed of drill).

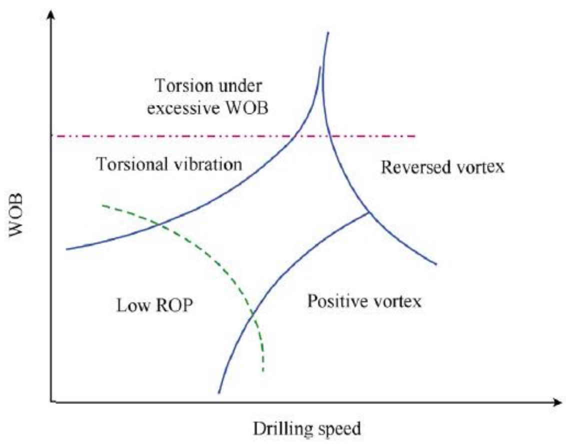


Figure 2. 10 - Diagram of the best area for downhole vibrations

2.2.3. Tracked vehicle vibration response considering the track circuit vibration

A tracked wheel machine is usually used in construction, landscaping applications and mine site. Tracks certainly have better traction, they steady any machine more than tires and offer greater talent to travel on the off-road surface, especially in up and down steep grades. Also, operation cost is higher but a crawler machine can work in every condition.

Yu Duan's article (12) was stated to correctly explain the vehicle vibration, the vibration response of the vehicle working principle affected by the track was considered. He established the track circuit model (Figure 2.11) by simplifying the rigid track then calculated constitutional vibration using Eigenvalue analysis.

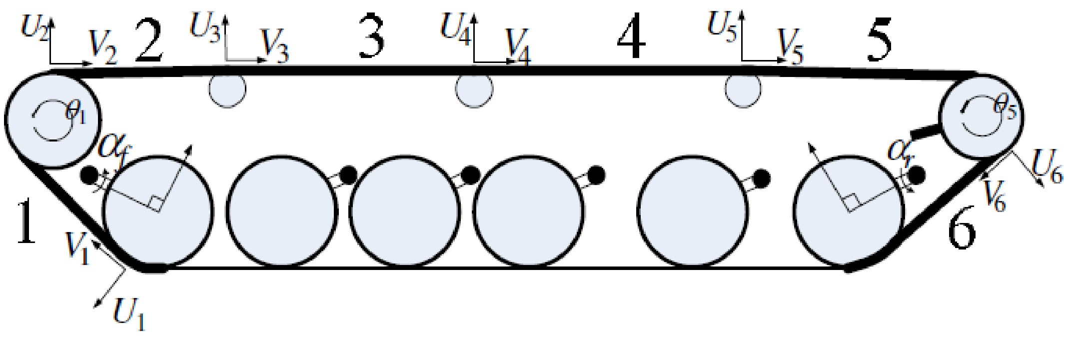


Figure 2. 11 – The track circuit model

The simulation method was to compare the dynamic model of flexible track (Figure 2.12 – "A") and the dynamic model of rigid track (Figure 2.12 – "B"). Then he checks the influence of track on the vibration of vehicle.

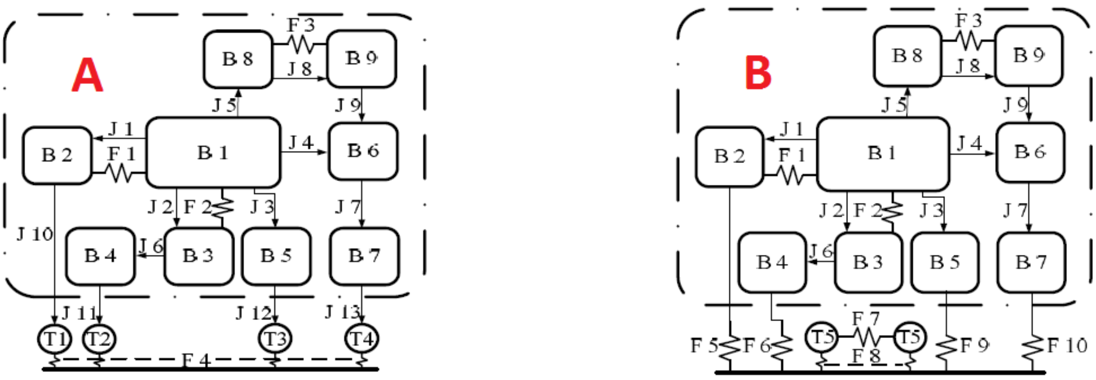


Figure 2. 12 – "A" Flexible track vehicle operation system topology diagram
"B" Rigid track vehicle operation system topology diagram

In the flexible track model, there are just kinematic constraints among the flexible track and the wheels. Therefore, in this model cannot take into consideration the complex vibration properties of the track. But in the rigid track model, the chain is constructed based on the geometrical dimensions. The connection between the chain and sprocket, idler, support roll and road-wheel are handled based on contact force. The chain joined by a track pin covered by a steel sleeve is restrained by the sleeve force (12).

His experimental method of article stated on Eigenvalue calculation of track circuit model. The natural frequency of the track circuit vibration is acquired by the boundary condition of free vibration, and Figure 2.13 is shown the natural frequencies of first five sort. The natural frequency range was 3-10 Hz and which fits to low frequency vibrations.

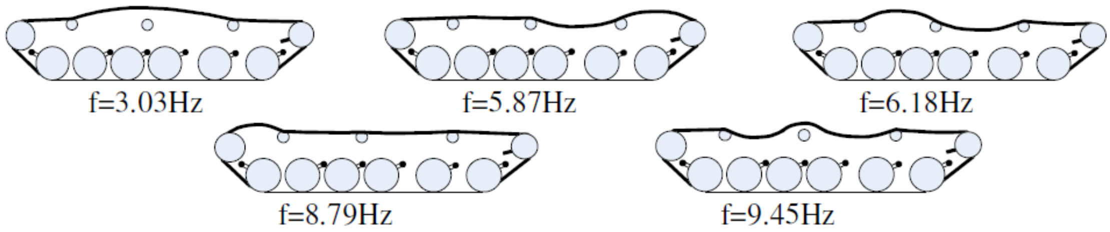


Figure 2. 13 - Vibration mode shapes.

During the vehicle driving on the off-road surface, it could head to low-frequency vertical vibration of the track circuit. As well as, result of analysis (12) verified the geometric and mechanical restraining influences of the track circuit mostly affect the low frequency vibration of the vehicle. And it could damage to vehicle.

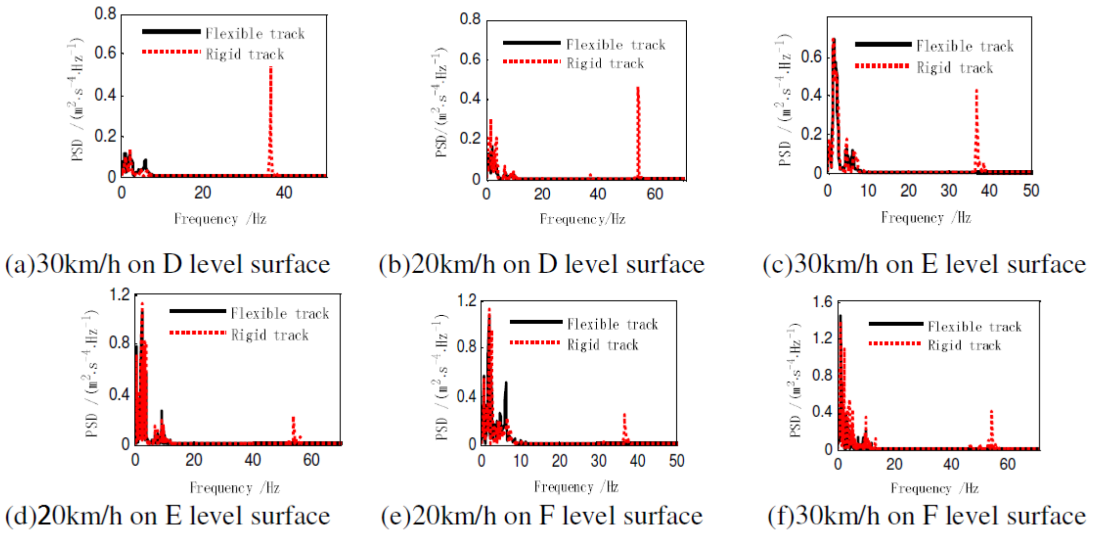


Figure 2. 14 – Comparison of vibration analysis under different road condition worst from D to E to F levels

Also, Figure 2.14 is displayed results of vibration analysis on road condition. Yu Duan (12) reported about results of experiment with speed increase or bad road conditions, the influence of the crawler vehicle vibration becomes progressively lower.

Chapter 3

This chapter will provide description of auger drilling rig (SBR-160A-24) and common issues of important parts that could cause in vibration. The chapter continues with the fundamental explanation methods of experiment and characteristic of vibration measurement equipment.

3.1. Important components of SBR-160A-24

Auger drilling machines are done with a helical screw with auger drill bit which is driven into the ground with rotation, the earth is lifted up the borehole by the blade of the screw and the auger drill bit. The basic kinematic scheme of the SBR-160A-24 is shown in Figure 3.1.

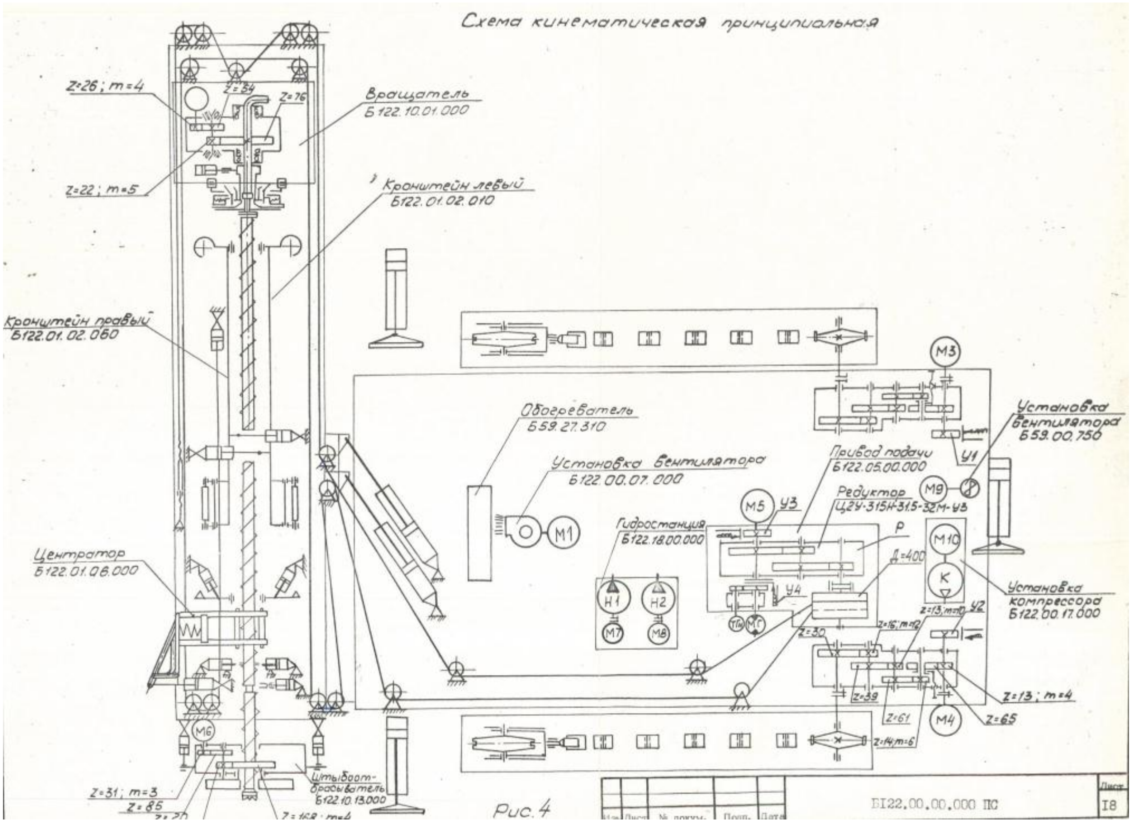


Figure 3. 1 – The kinematic scheme of the SBR-160A-24

The drive of the machine is electric. To drive some mechanisms used hydraulics. The rotation of the drilling tool is transmitted from the rotator (Б122.10.01.000) with a three-speed asynchronous motor and gearbox. Changing the frequency of rotation of the drill rod is done in steps by switching the number of pairs of poles of the engine using a standard magnetic station.

The connection of the spindle with the drill rod is provided with a cam chuck. The rods are interconnected by semi-automatic locks, the latches of which are placed in the hexagonal shank of the rods. When assembling and disassembling the drill, it is held by a hydraulically powered fork. Reliable centering of the rod is provided by a centralizer (Б122.01.06.000), opening the lock - two hydraulic cylinders. The mechanism for supplying the drill rod to the bottom is not structurally integrated into one whole and consists of a number of elements: a feed drive, guide rollers, blocks and a rope.

The drive for feeding the descent and lifting of the tool is carried out from the M5 electric motor ‘M5’ (raising of the rod) and hydro motor ‘MГ’ (feed to the bottom hole) through the gearbox ‘P’. From the drive, the force of feed or lift is transmitted through the rope, the switching rollers and blocks on the frame, the system of blocks on the mast and the rotator. The spreader is powered by an electric motor ‘M6’. Through a two-stage gear. Compressor ‘K’ is driven directly from an asynchronous motor ‘M10’. The fan engine room is driven by an induction motor ‘M9’. The track of the machine is driven by engines ‘M3’ and ‘M4’ through helical gearboxes. The motor is an asynchronous rotator, three-speed, provides rotation of the drill rod with a frequency of 100, 130 and 200, on its shaft is installed gear drive gear.

3.1.1. Drill Rod

The SBR-160A-24 machine differs in full, mechanization of assembly and disassembly of a drilling rod. For this, the rods are equipped with semi-automatic locking connection. The BR-160A-24 is belong to CFA piles drilling groups.

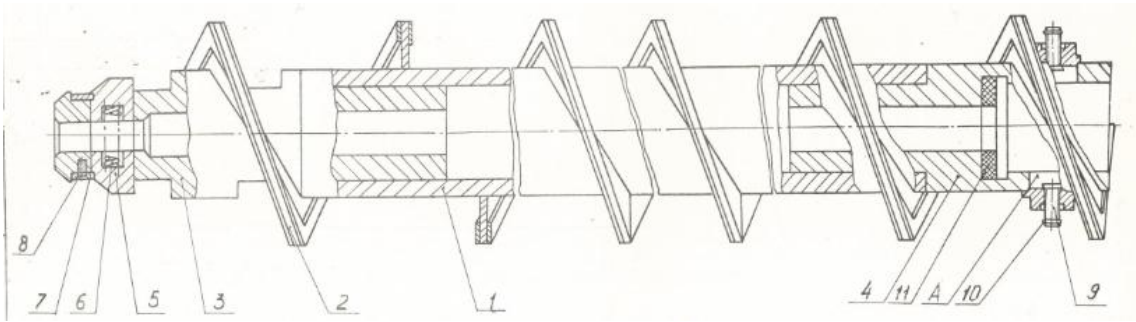


Figure 3. 2 – Drill Rod

In Figure 3.2 is shown the scheme of drilling rod. Which consists of 1 - pipe, 2 - helix, 3 - hexagonal shank, 4 - couplings, 5 - latches, 6 - springs, 7 - bars, 8 - fixed, 9 - fingers, 10 - with rings, 11 - and seals.

Longitudinal through channels in the shank and coupling ensure the passage of compressed air into the well. When connecting rods, the shank ‘3’ enters the sleeve ‘4’. The end of the coupling acts on the bevels of the latches and sinks them, compressing the spring ‘6’. When drilling, the hexagonal section of the shank provides torque transmission. The axial force is transmitted through the ends of the rods, and during lifting these efforts are perceived by the latch.

This machine drill from 20 to 25 holes in one day. The rod of drill is replaced three times per 1000-meter drilling. Single rod is a very expensive. That is why engineers of Baganuur LC found technique which is they coated rod to use welding method. Figure 3.3 is shown this method and it is to reduce wear off time of drill rod. As workers said one rod coating process spend 2.5 kg welding electrode. Obviously, it is cheaper and economical decision than replaced by a new rod. Nevertheless, it takes a lot of time and adds workload on workers.

Figure 3. 3 – Welded drilling rod

The reasons of easy wear off the drill rod are for a several external and internal influence. For example, rotational speed of electric motor is constant which cause difficulty on to drill hard soil. It produces high vibrations and creates to wear off rod bits.

In generally, when vibration cause in machine another part could damage which is increasing a chance of facing problems.

3.1.2. Hydraulic Jack

The SBR-160A-24 machine has four hydraulic jacks. In Figure 3.4 shows the device jack. The jack consists of 1 - Cartridge (a container that is used in a larger piece of equipment), 2 - Sliding cylinder, 3 – Piston, 4 – Base, 5 – Bushing, 6. 7. 8 - Bolt caps, 9 - Pipeline of hydraulic liquid.

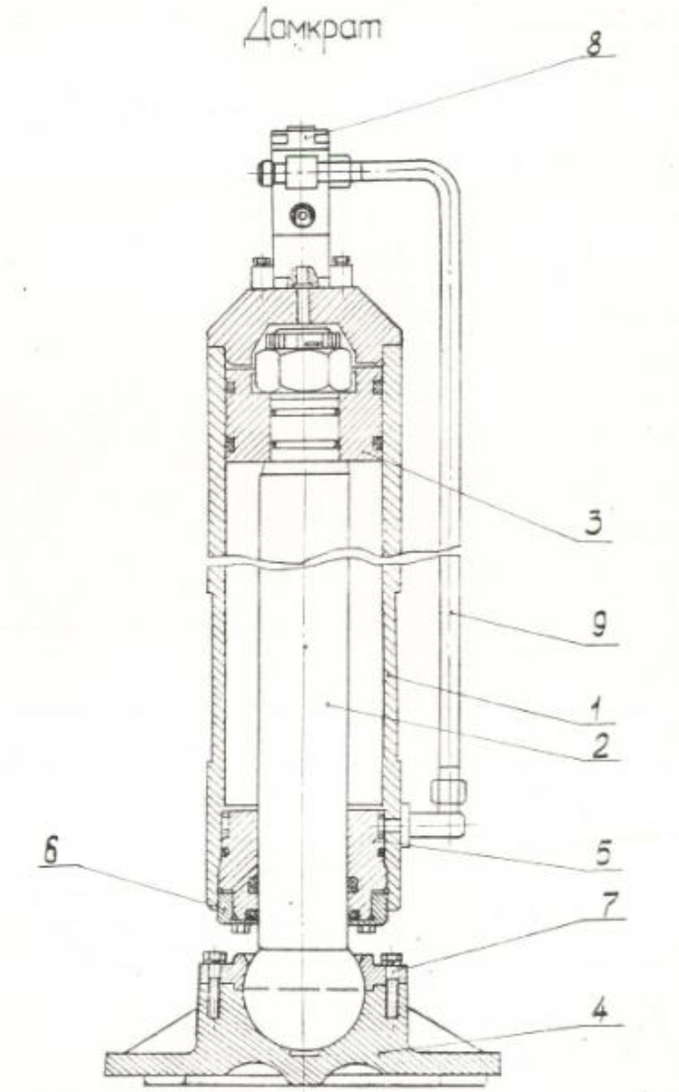


Figure 3. 4 – Hydraulic Jack

The usage of this jacks is to support (stabilizer) during the drilling process. Certainly, it can help to decrease vibrations while the drilling process. However, in Baganuur LC, the hydraulic jacks don't perfectly work. When the jack is moving upward and downward this movement is very slow. Only downward motion is to take around 10-13 minutes. That means, it also takes a lot of time and it can change work schedule and order. Then they don't use that jacks which leads to increase a vibration during the drilling process. Surely, the high vibrations effect on drill rod then it is one of the reasons to wear off the drill bit.

There has a several reasons of slow movement in hydraulic jack (13). Such as:

- Leaking seal: An inaccurately fitted seal leads to leak liquid of cylinder.
- Corroded barrel: This kind of failure is created by water or other worst impurities in the oil/liquid.
- Damaged or bent piston rods or rod bearings: This kind of operational problem could be caused by a misalignment between the load and the cylinder.
- Overheated cylinder: If a cylinder is working in hot condition it can damage seal compound.

– Lack of services: Workers are to check the lubrication of cylinder in everyday to choose suitable lubricants on the device.

3.1.3. Crawler of SBR-160A-24

The crawler (Figure 3.5) consists of a 1 – track tape, a 2 – beam, a 3 – tension mechanism, 4 – rollers and a 5 – driving wheel. The two tracks are interconnected by frame and nuts. Drives are hinged to the frame in brackets with covers. Earrings and fingers drives are attached to the frame when dismantling the course. The drive shafts are connected about the shafts of the driven wheels of the carriages with gear couplings.

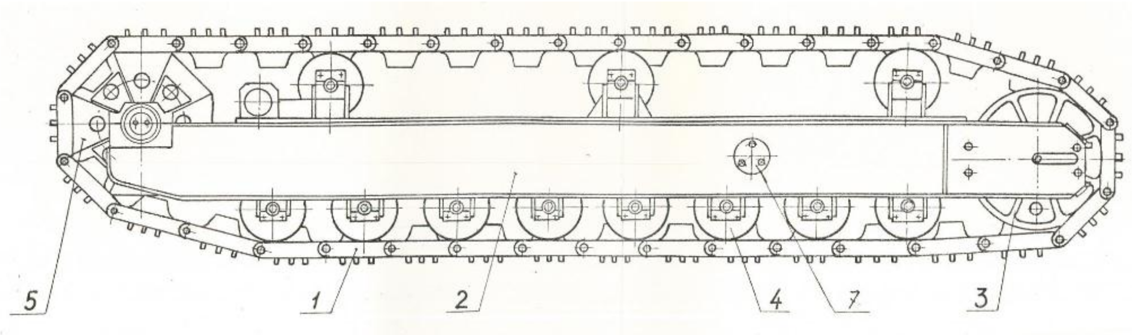


Figure 3. 5 – Crawler scheme of SBR-160A-24

Tracks certainly have better traction, they steady any machine more than tires and offer greater talent to travel on the off-road surface, especially in up and down steep grades. Generally, the SBR-160A-24 machine is using in Baganuur LC since 1986. It is very old machine and nowadays, the components of that are outdated and deteriorated. For instance, the tracks are one of them. The reason is the problems caused in track system.

Figure 3. 6 – The problems of track system

That is the braking system was deteriorated. Figure 3.6 is provided the machine cannot brake and lock the track system. The rod is highlighted by the red circle (in Figure 3.6). The purpose of that rod is to lock the track system during the drilling process. Obviously, that is to influence on vibration of the machine and to increase them.

3.2. Measurement method

3.2.1. The vibration measurement equipment

In this thesis, the measurement part is to measure the vibrations of drilling machine. It was used by vibration tool 'Roga Plug.n. DAQ' (Figure 3.7). This equipment has a dual input and output for the purpose of recording and analyzing the signal, and it is directly connected to the USB1.1 input of the computer, so it does not require special devices and feeds.

Figure 3. 7 - The vibration measurement equipment

Figure 3. 8 - The accelerometer sensor

The tool is the vibration measurement of time domain function data is saved in ASCII format and operated by DeweSoftX2 program. The interface DeweSoft program is designed to take the vibration function from the vibration measurement device connected to the accelerometer sensor (Figure 3.8). The accelerometer which is used in the test, is shown technical specification in (Appendix A – “Table 3.1”).

3.2.2. Methods of measurement

The measurement was done at several locations. First one was in a control room of the auger drilling rigs. Second one was on the electric supply cover and last was near by the electric motor in an engine room of that machine. In Figure 3.9 is shown a general scheme of measurement processing. The measurement method was following order:

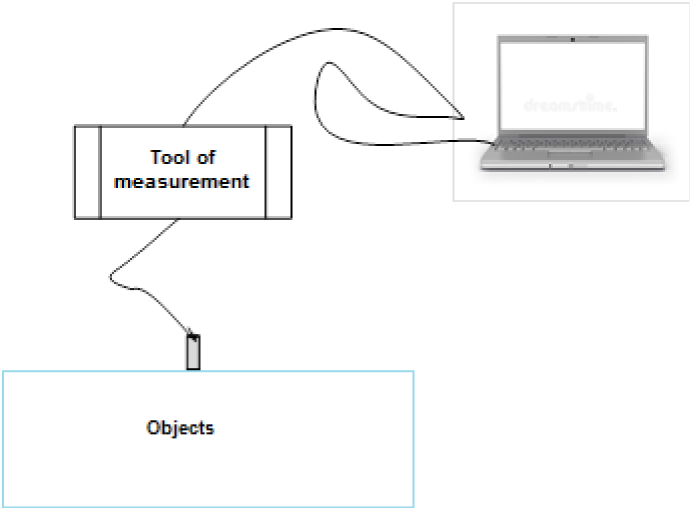


Figure 3. 9 – Scheme of Measurement process

1. Checked the integrity of the accelerometer sensor before measuring
2. The accelerometer located be stationary at the position of the measuring object.
3. The cable of accelerometer was connected in input IN1 of the vibration measurement device.
4. The USB cable of device connected in a laptop (program installed) then vibration device turned on.
5. Therefore, the software adjustment of device did on laptop. For example, amplitude, voltage and current.
6. Finally, the signals of vibration recorded and saved by using DeweSoftX2 program.

As well as, the experiment was done following cases. Such as, when the drill was starting hole, when the drill was pulling back to upward, and when the drilling machine was changing the position of next borehole drilling.

Chapter 4

This chapter will present about data collection and their analysis of the vibration measurement. Then result section will explain and introduce of the vibration reducing device. The following chapter will continue with discussions.

4.1. Data collection and Analysis

The vibration data was taken in the soft soil drilling process, it was recorded in DeweSoftX2 program and the graph was drawn in Microsoft Excel. In generally, in the graphs: the vertical axis - Amplitude of vibration and the horizontal axis - Frequency of vibration.

First measurement location was in a control room of the SBR-160A-24. 2. The accelerometer was located be stationary at the position of the control panel. Figure 4.1 is shown the graph of the vibration on that position.

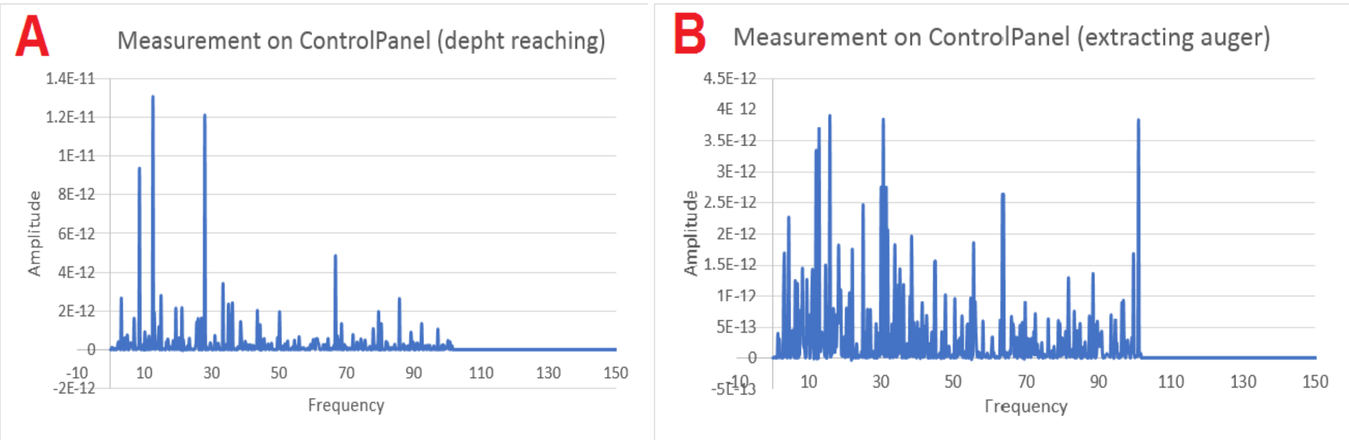


Figure 4. 1 – Measurement on Control panel

In graph "A" will provide a data of vibration measurement on control panel. And measurement was done during the drilling process which was auger drilling depth reached into borehole. Whereas, in graph "B" will show measurement data of during the extracting auger. As seen from the graph "A" and "B", the amplitude is relatively lower. Also, we can see the vibration of to drill hole is lower than the vibration of to extract auger. The both graphs are presenting the vibration amplitude is decreasing after some duration and which is almost zero amplitude.

Second measurement location was in an engine room of the SBR-160A-24. The accelerometer was located be stationary at the position of the electric supply cover. Figure 4.2 is shown the graph of the vibration on that position for the primary drill.

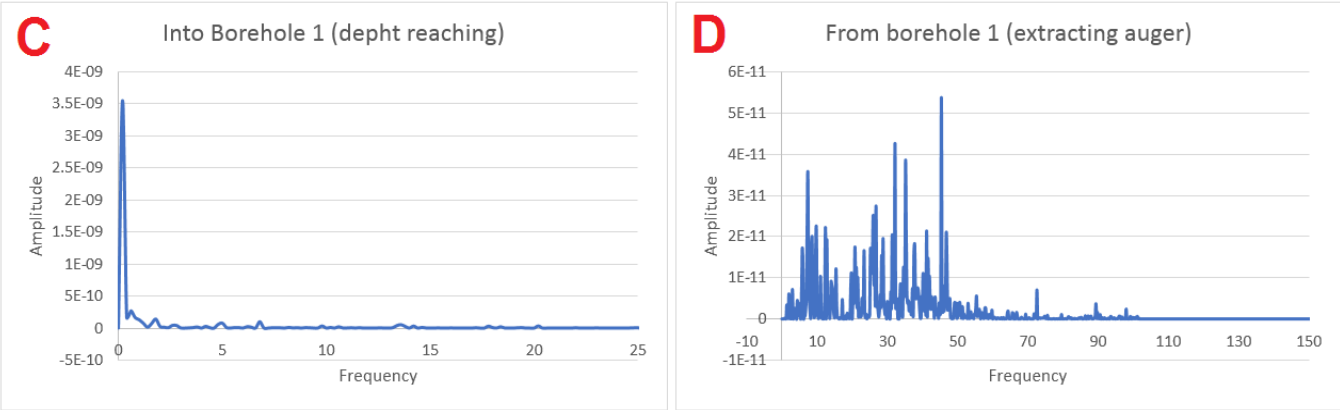


Figure 4. 2 – Measurement on the electric supply cover (Primary drilling)

In graph “C” will indicate the primary drill and auger drilling depth reached into borehole. Rather, in graph "D" will give measurement data of during the extracting auger.

However, in Figure 4.3 is shown the graph of the vibration on that position for the secondary drill.

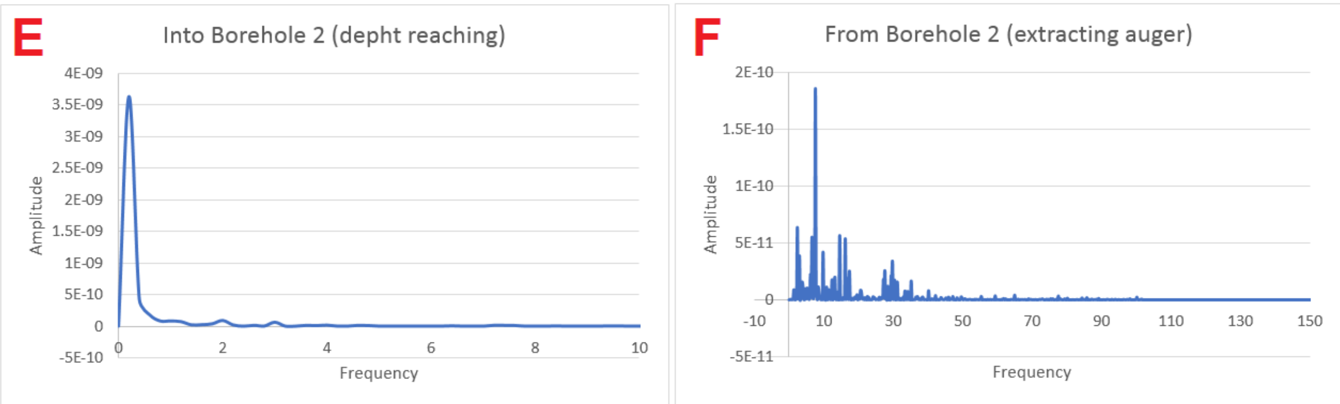


Figure 4. 3 – Measurement on the electric supply cover (Secondary drilling)

In graph “E” will provide secondary drill and auger drilling depth reached into borehole. But, in graph “F” will show vibration data of during the extracting auger. From those graphs, we can see vibration amplitude decreasing when the drilling depth increasing. For example, data of graph "C" and "E" will display when the drill process starts vibration suddenly increased then quickly decreased it. The reason of that, the rotational speed of motor is a faster and cannot control it. Because, motor speed is a constant and there doesn’t have any control system. On the other hand, machine starts reverse direction drilling for extracting the auger after reaching the wished depth drilling.

For example, data of graph "D" and "F" will show during this time vibration amplitude is higher than vibration of auger drilling depth reached into borehole. These kinds of vibration could come from the drill without any stabilizer of drilling machine.

Additionally, as a result of measurement of vibration Figure 4.2 and Figure 4.3 are compared:

For the primary drilling - vibration amplitude and frequency are higher

For the secondary drilling - vibration amplitude and frequency are lower

Finally, from Figure 4.4 will present the vibration measurement data of soft layer '1' and strong sandstone layer '2'. From those 2 graphs, we can see their vibration amplitude is different from each other. For example, graph '1' will provide amplitude is almost zero and it means vibration is a lower during the drilling on soft layer. On the other hand, graph '2' will provide the vibration amplitude is a very high compared with graph '1'. As well as, the amplitude value is quite close to resonance value especially when drilling process starting. But graph '2' is also to prove the vibration amplitude decreasing when the drilling depth increasing.

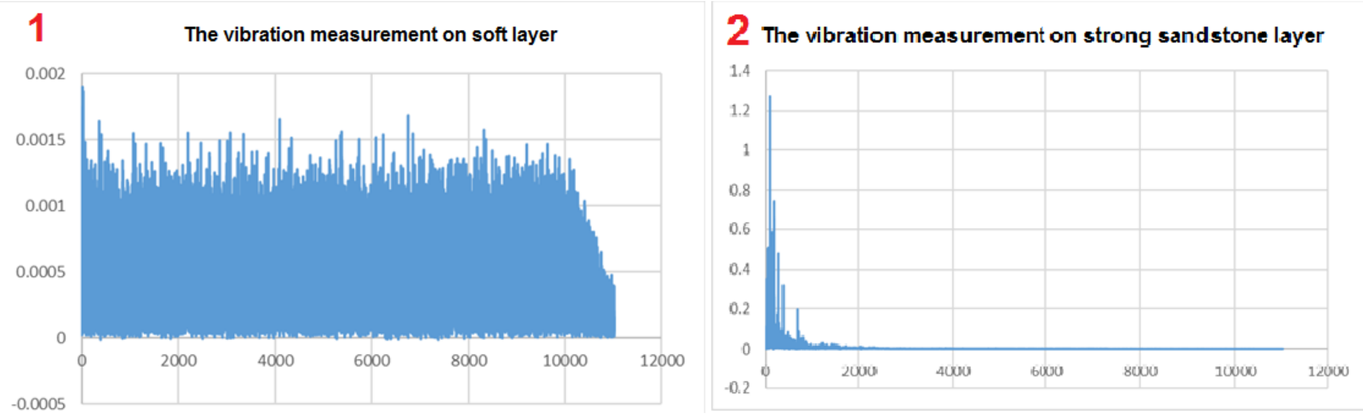


Figure 4. 4 – The vibration measurement on different layers

From these analysis results, we can see the vibration is relatively high and to need solution for reducing the vibration.

4.2. Results

From the vibration analysis of the SBR-160A-24, the vibration amplitude is to cause unsuitable condition. Thus, results of vibration analysis were the monitoring system doesn't work and directly should reduce the vibration. The hydraulic jack (stabilizers) of that machine can help to decrease vibrations during the drilling process. However, stabilizers don't perfectly work. When it is to move upward and downward this motion is very slow. For this reason, the company believes that productivity of operation decreases. And mostly, they don’t use these stabilizers. Accordingly, this thesis is suggesting the electric cylinder stabilizer for the company.

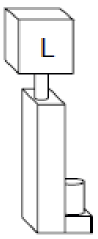
4.2.1. Calculation of Electric Cylinder

The application (SBR-160A-24) has the following defined data:

Weight = 28000 kg
Stroke length = 1.2 m = 1200 mm
Move time = 3 minutes = 180 sec
Orientation: Vertical

Trust calculation (14)**:** Total thrust generally consists of acceleration thrust (F_a), thrust due to gravity (F_g) and thrust due to friction (F_f).

$F_a = ma$ [5] $F_g = ma\ sin\alpha$ [6] $F_f = \mu_s ma cos\alpha$ [7]



Vertical equation for Total Thrust (F_t):

$$F_t = F_a + F_g + F_f \quad [8]$$

Figure 4. 5 -Cylinder Orientation

Velocity (V) is calculating the trapezoidal velocity profile (Figure 4.6).

$$V = 1.5 * \frac{D}{t} = 1.5 * \frac{1200\ mm}{90\ sec} = 10\ mm/sec \quad [9]$$

$$a = 4.5 * \frac{D}{t^2} = 4.5 * \frac{1200\ mm}{(90\ sec)^2} \approx 0.1667\ mm/sec^2 \quad [10]$$

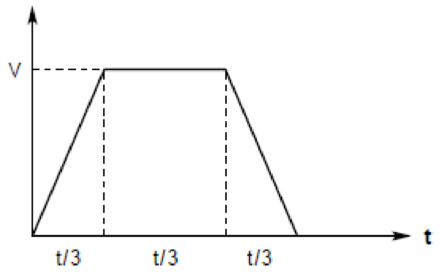


Figure 4. 6 – Trapezoidal motion profile

From the equation [5] acceleration thrust (F_a) is 4667.6 N, the equation [6] force of gravity (F_g) is 274680 N, friction force (F_f) (neglected because vertical loading) is 0 N and the equation [8] total thrust (F_t) is to become 279347.6 N. Four electrical cylinder stabilizer need in the drilling machine. Thus, a single stabilizer will load around 70000 N.

Torque determination (14)**:**

$$\tau = \frac{Thrust*Lead}{\eta_s*\eta_b*2\pi*Ratio} \quad [11]$$

The screw shaft is chosen a ball screw. Which utilize recirculating ball bearings rolling between the screw and nut. This is a much greater efficient screws (generally 90%) and low sliding friction. Ball screws can work at 100% duty cycle. Lead screws have a maximum rotational velocity that is a function of the screw diameter and the distance between its bearing supports. In that case, screw lead is taken 20 mm and gear ratio is considered 8:1. From the equation [11] maximum torque (τ) is around 130 Nm.

Motor speed determination (14)**:**

$$Speed = \frac{V*Ratio}{Lead} \quad [12]$$

The required motor speed is calculated from the equation [12] and value is 240 rpm.

$$\omega = rpm * \frac{2\pi}{60} \quad [13]$$

The needed angular speed is considered from the equation [13] and value is 25.1 rad/sec.

$$P_{out} = \tau * \omega \quad [14]$$

Output mechanical power of the motor could be calculated by using the equation [14] and which is about 3.3kW.

4.2.2. Selection and Modelling of Actuator

From the calculation, the model of the electric cylinder stabilizer was produced and drawn in Autodesk Inventor drawing program. In Figure 4.7 is shown 2D sketch of electric cylinder stabilizer and which consist of following views.

1. Right side view of the cylinder
2. Bottom view of the cylinder
3. Top view of the cylinder with electric motor

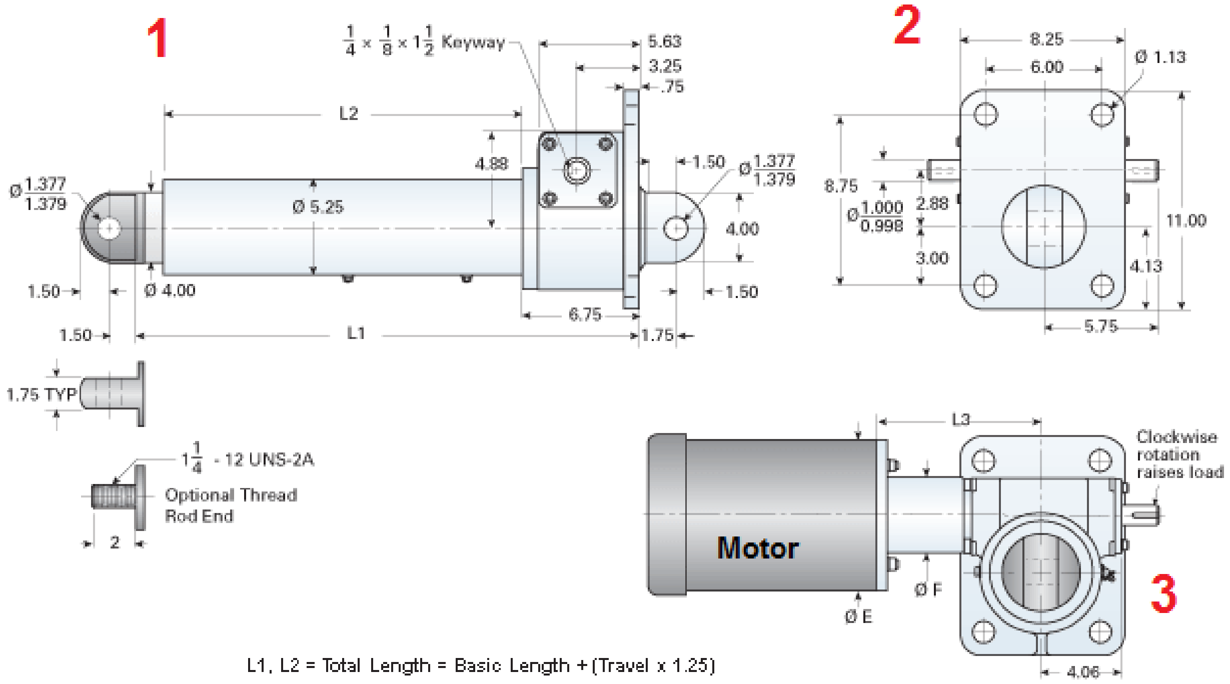


Figure 4. 7 - 2D sketch of electric cylinder stabilizer

Design of the cylinder is a single reduction electric cylinder. Which consists of only one one couple of gears. They are called worm gears. In Figure 4.8 is shown precisely inside components of electric cylinder. They are intersecting shafts vertical directed 90 degrees to each other. Their purpose is to convert from a horizontal axial movement to a vertical axial movement and to offer high reduction ratio. Such as, from the calculation gear ratio is calculated 8:1. As well as, a reduction gears are applied, which reduces the high-speed motion of the electric motor into low revolution per minutes (rpm) range required by the oriented shaft.

Figure 4. 8 - Inside view

Four electric cylinders are needed for the SBR-160A-24. These four cylinders should connect like a U-arrangement type (Figure 4.9).

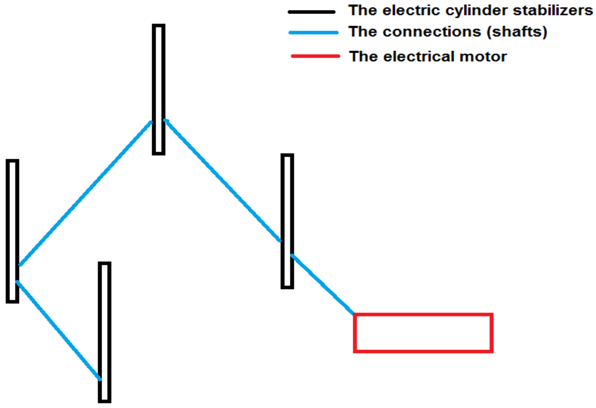


Figure 4. 9 – Scheme of the 'U arrangement'

In Figure 4.10 will provide the 3D sketch of electric cylinder connected with motor in the 'Autodesk Inventor' program.

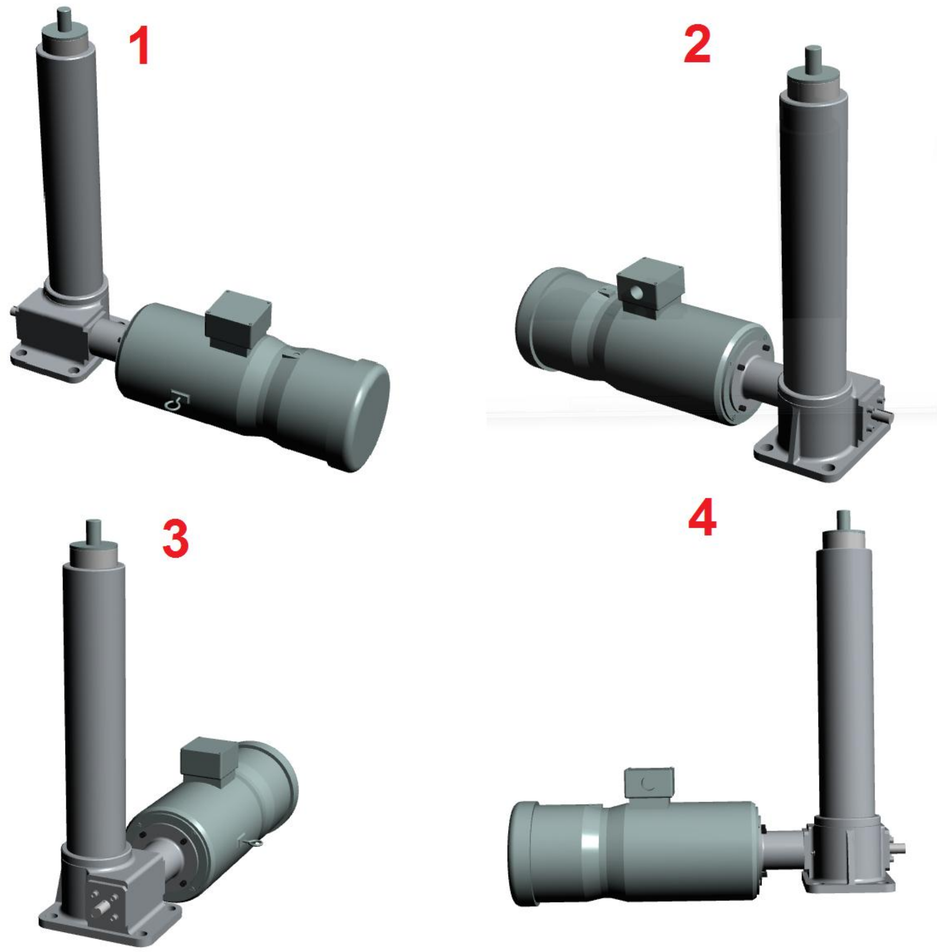


Figure 4. 10 – 3D sketch of the electric cylinder with motor

4.3. Discussions

As a result of the measurement and analysis, the vibration is relatively high during the drilling process. There are number of reasons for producing the vibration. For example, from electrical motor, from crawler of the drilling machine, from where and what kind of material to drill and from the usage of hydraulic jacks (stabilizers). Therefrom, the main source of vibration is the hydraulic jack and it does not have perfect and smooth working principles. Which means, the movement (upward and downward) of stabilizers is a very slow. Only downward motion is to take around 10-13 minutes. The company believes that productivity of operation decreasing. Thus, they don't use that jacks which leads to increase a vibration during the drilling process. There has a following reasons can influence on working principle of the stabilizers.

- Firstly, the auger drilling rig SBR-160A-24 is old technology. Due to long-term operations, equipment's component has deteriorated. Such as, the hydraulic pipes (the hoses) are important part of hydraulic jack. And the fluid of stabilizers is transmitted by that pipes. But the fluid is not passed through perfectly by the hoses. Because the inner tube of the hose is showing signs of swelling and is badly deteriorated. It leads to the hydraulic piston does not pressurized fully and the fluid doesn’t enough to moving piston of hydraulic stabilizers.
- Secondly, the weather conditions are influence on flawless working of stabilizers. It means, Mongolian winter is a very harsh and cold (sometimes up to -40 Celsius). It effects on fluid viscosity and temperature. In coldest condition, the hoses cannot transmit and compress anymore fluid.
- Thirdly, the compressor physical properties can influence to press the piston of hydraulic jack. The reason why, the compressor power does not enough to transmit the fluid.

From that reasons, the vibration reducing solution founded and there some calculation and analysis of modelling done as needed in this research. The modelling and design were based on the electric cylinder stabilizer. And they use especially in heavy duty applications. Electric cylinders get the rotational force of a motor (electrical energy) and apply it into linear movement (torque). There don’t have any fluid effect for the load but there have vertical screw and nut inside of the cylinder. General working principle is the nut will move in a line up and down, creating the push/pull it leads to load. The main benefit of electric cylinder is easy to control velocity. It can work precisely and accurately move in sync and to save time for loading. As well as, the weather condition doesn't influence on overheat and cold temperatures, and never leak hazardous fluids. Obviously, the equipment depends on following characteristics (It was calculated on section 4.2.1):

- **Screw type:** A ball screw
- **Motor size:** 3.3 kW
- **Motor rotational speed:** 240 rpm
- **The total load:** around 280 kN (a single cylinder to load 70 kN)
- **The reduction mechanism:** using a worm gear (It is single reduction)

Chapter 5

This chapter will conclude the research work and provides recommendations and suggestions for future development of the suggested techniques.

5.1. Conclusion

A background investigation was conducted into the main causes of the vibration, how to effect on the auger drilling rig (SBR-160A-24) and to resolve those issues, what kind of solution and methods there have. Furthermore, the auger drilling machine's important parts and their fundamentals, including their damages of equipment, major sources and prevention methods have been studied. And corresponding possible solutions are provided in the results and analyzation section.

The experiment part is to measure the vibrations of drilling machine. It was used by vibration tool 'Roga Plug.n. DAQ'. That device is based on DeweSoftX2 program. This program is the most advanced data acquisition, recording and analysis software. As a result of the experiment were detected the vibration is a high. The main cause can be a hydraulic jack (stabilizer) of the drilling machine. Then electric cylinder was redrawn in 3D version by using Autodesk Inventor and calculated required application data.

Design modification in the drilling machine is to reduce the vibration and to save operation time and costs (the movement of old technology is a very slow). Obviously, the vibration decreased means to reduce abrasive wear in drilling bit. Eventually, a monitoring system with smart sensors can installed in SBR-160A-24. There will create suitable environment for to work that monitoring system.

5.2. Suggestion

There are still a number of open topics about to reduce the vibration for future research in advancement and upgrading of drilling machine's important part. The further researcher's requirement is to improve combined experimental and theoretical study on vibration measurement and reducing technology for the vibration in another efficient ways. As much as possible, researcher should make some simulation on the own design.

Such as, from the electric motor's side, how can reduce vibration, what types of motor have a low vibration and what kind of improvement can make on electric motor etc. From the tracked wheel (crawler) side, what kind of improvement can make on their rollers and driving wheel. Also, researchers should study about vibration difference between normal wheel and tracked wheel (crawler) for the drilling machine.

References

1. ICRC. Technical Review Borehole Drilling and Rehabilitation Under Field Conditions. Tech Rev Boreh Drill Rehabil Under F Cond [Internet]. 2010;1(2):130. Available from: https://www.icrc.org/eng/assets/files/other/icrc_002_0998.pdf

2. An introduction to machinery vibration [Internet]. [cited 2019 Apr 22]. Available from: https://www.reliableplant.com/Read/24117/introduction-machinery-vibration

3. 6 common causes of machine vibrations — Istec International [Internet]. [cited 2019 Apr 22]. Available from: https://www.istec.com/en/6-common-causes-of-machine-vibrations/

4. Morgan W. Vibration Analysis of an Electric Motor Fan Assembly. SAE Tech Pap Ser. 2010;1(July 1999).

5. Ágoston K. Fault Detection of the Electrical Motors Based on Vibration Analysis. Procedia Technol. 2015;19:547–53.

6. TROUBLESHOOTING MOTOR UNBALANCE - VibrAlign [Internet]. [cited 2019 Apr 24]. Available from: https://vibralign.com/other-topics/troubleshooting-motor-unbalance/

7. Causes of unbalance in rotating machinery | AMP Maintenance Forums [Internet]. [cited 2019 Apr 24]. Available from: https://www.maintenance.org/topic/causes-of-unbalance-in-rotating-machinery

8. Holopainen TP. Electromechanical Interaction in Rotor Vibrations of Electric Machines. 5th World Congr Comput Mech. 2002;7–12.

9. William R. Finley, Mark M. Hodowanec WGH. An Analytical Approach to Solving Motor Vibration Problems. IEEE Trans Ind Appl. 2000;36(5):2000.

10. Wani AS, Sagavkar GS, Bhate VK, Mumbai N. Vibration analysis of drilling operation. 2013;1(April):163–75.

11. Zhu Q, Zou Z, Huang B, Ma L, Xia J. Downhole vibration causing a drill collar failure and solutions. Nat Gas Ind [Internet]. 2016;36(12):80–6. Available from: http://dx.doi.org/10.1016/j.ngib.2017.07.013

12. DUAN Y, RUI Q, WANG H. Analysis of Tracked Vehicle Vibration Response

Considering the Track Circuit Vibration. DEStech Trans Eng Technol Res. 2018;(icmca):34–9.

13. 5 common causes of hydraulic cylinder problems | TheSpec.com [Internet]. [cited 2019 Apr 29]. Available from: https://www.thespec.com/shopping-story/8139008-5-common-causes-of-hydraulic-cylinder-problems/

14. Index E, Products EA. Electromechanical Actuator Products ET Series Electric Cylinders Eng and Selection ET Series Electric Cylinders. 1894;66–84.

15. Iiia III, Iva I V, Vi V, Vii V, Viii V. Классификация горных пород по крепости f (шкала проф. М. М. Протодьяконова) Наиболее распространенная классификация горных пород по крепости, составленная профессором М.М. Протодьяконовым в начале XX века.

Appendix A

The most common classification of rocks by fortress, compiled by Professor M.M. Protodeacon at the beginning of the 20th century (15).

Category of Rock	Rock Strength	Rock	Rock Coefficient, *f*
I	Extremely strong	Extreme strong quartz and basalt rock...	20
II	Very strong rock	Very strong granite, quartz, porphyry, siliceous shale	15
III	Strong rock	granite, very strong sandstone/limestone /iron ore, strong conglomerate	10
III a	Strong rock	limestone (strong), loose granite, strong sandstone / marble, dolomite, gneiss	8
IV	Intermediate strong rock	Sandstone, iron ore	6
IV a	Intermediate strong rock	Sandy shale, shaly sandstone	5
V	Intermediate rock	Strong loamy shale, loose sand-limestone, soft conglomerate	4
V a	Intermediate rock	Loose shale, marl	3
VI	Intermediate soft rock	Soft shale, very soft limestone, chalk, halite, gypsum	2
VI a	Intermediate soft rock	Gravel soil, fractured shale, strong coal	1.5
VII	Soft soil	Strong clay, soft coal	
VII a	Soft soil	Sandy clay, loess, gravel	0.8
VIII	Soil	Humus, peat, humid sand	0.6
IX	Loose soil	Sand, fine gravel, loose ground extracted coal	0.5
X	Fluent soil	Marshy soil, watery loess	0.3

Table 4 - The coefficient of strength f on a scale of prof. M.M. Protodyakonova

The technical specification	Data
Model	YMC121A100
Sensitive (±5%)	100 µB/gr
Frequency range (±5%)	0.5-8 kHz
Resonance frequency	≥ 40 kHz
Overload limit	5000 m/s^2
Temperature range	-50 +121 ^0C
Voltage of source	18 – 30 V (constant voltage)
Constant current of source	2 – 20 mA
Output resistance	<100 ohm
Electricity separation	>10^8 ohm

Table 5 – The technical specification of accelerometer

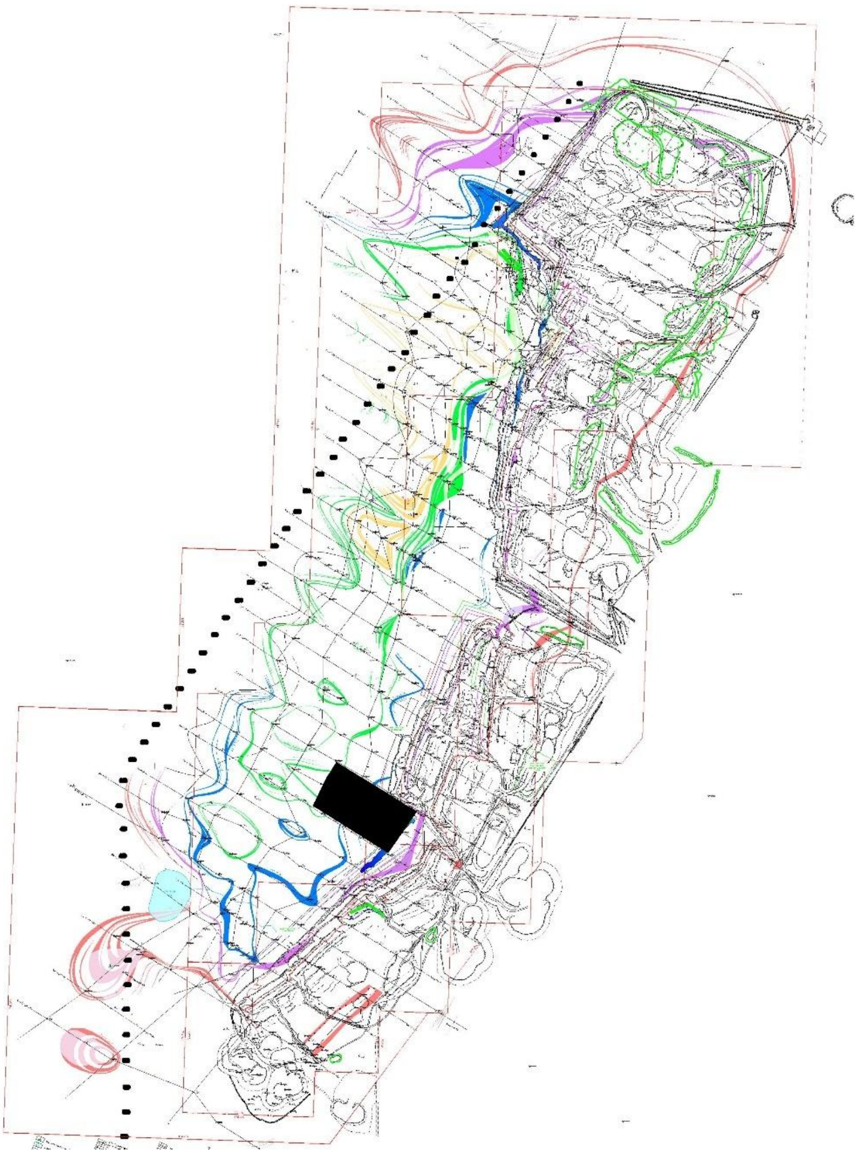


Figure A. 1 – Geometrical map of the 'Baganuur LC' coal mine deposit

Figure A. 2 - The drilling rod extending process

Figure A. 3 - The auger drilling rig (SBR-160A-24)

Appendix B

This appendix provides additional information which are consist of some definitions.

- **Parallel misalignment:** The shaft center lines are parallel but are not in line. This can be both horizontal and vertical. Parallel misalignment is also known as offset misalignment (3).
- **Angular misalignment:** The shafts meet at a point, but are not parallel. This can be both on the horizontal and vertical axis. Angular misalignment is also known as gap misalignment (3).
- **Combined parallel-angular misalignment:** A combination of both parallel and angular misalignment. Combined parallel-angular misalignment is the most common misalignment (3).