GEOTHERMAL ROCKS COMPRESSIVE STRENGTH EVALUATION DURING DRILLING OPERATION

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Keywords: geothermal drilling, compressive strength, drilling parameter

ABSTRACT

Geothermal well drilling design is considered based on the rock strength inside the wellbore. One of rock strength parameter that analyzed in this study is rock compressive strength. Several methods have been developed to determine rock compressive strength by using laboratory core sample test. Empirical correlation to calculate rock compressive strength by using drilling data has been widely developed in oil and gas industry. Meanwhile, those empirical correlation has not yet developed and required adjustment for geothermal field. Those calculation are can be used as the initial interpretation, particularly in exploration wells, by using real-time geothermal drilling data processing.

This study was conducted to predict the rock compressive strength in water dominated geothermal field using the analysis of drilling data in Mud Log Unit (MLU). The rock compressive strength is approached by analyzing the drilling parameter trend such as Rate of Penetration (ROP), Weight on Bit (WOB), and Revolution per Minute (RPM). Corrections are performed by analyzing the bit used in each section, geothermal rocks lithology, wellbore design, and drilling operation conditions.

Rock compressive strength prediction can be done by using the reference of common geothermal rocks physical properties encountered in association with volcanic area such as andesite, breccia, tuff, and rhyolite[4]. The correlation between rock compressive strength and drilling parameter is evaluated at particular section. Those evaluation can improve the performance and future development drilling design.

1. INTRODUCTION

Geothermal system in Indonesia is commonly associated with volcanic area. The volcanic geothermal system characteristics classified as a high temperature reservoir about >225ºC. Most of the geothermal rock encountered in volcanic area are igneous and metamorphic rock. Generally, geothermal rock have very hard rock strength ranging between 100-250 MPa[4].

Knowledge about rock in-situ and wellbore stress condition used to predict the wellbore stability. Wellbore stability that achieved has purpose to overcome the wellbore problem as well as minimizing drilling time and cost. In-situ stress and wellbore stress are influenced by the rock strength parameter.

One of the geomechanics properties determined in this study is rock compressive strength. Rock compressive strength is able to be measured directly in the laboratory using rock samples from the wellbore or indirectly using rock physical properties and drilling data. Rock physical properties related to compressive strength is density, porosity, and permeability. In addition, drilling data such as drilling performance and hole problem can predict rock compressive strength qualitatively and quantitatively.

2. METHODOLOGY

In this paper, the new methodology is introduced to predict the rock compressive strength in geothermal field. The approach of this methodology is based on literature study and analyzing the correlation between drilling data and compressive strength by plotting ROP, WOB, RPM data vs. depth. Then, the corrections are performed by analyzing the bit used in each section, geothermal rocks lithology, wellbore design, and drilling operation conditions. This methodology of study is presented as flowchart in **Figure 1**.

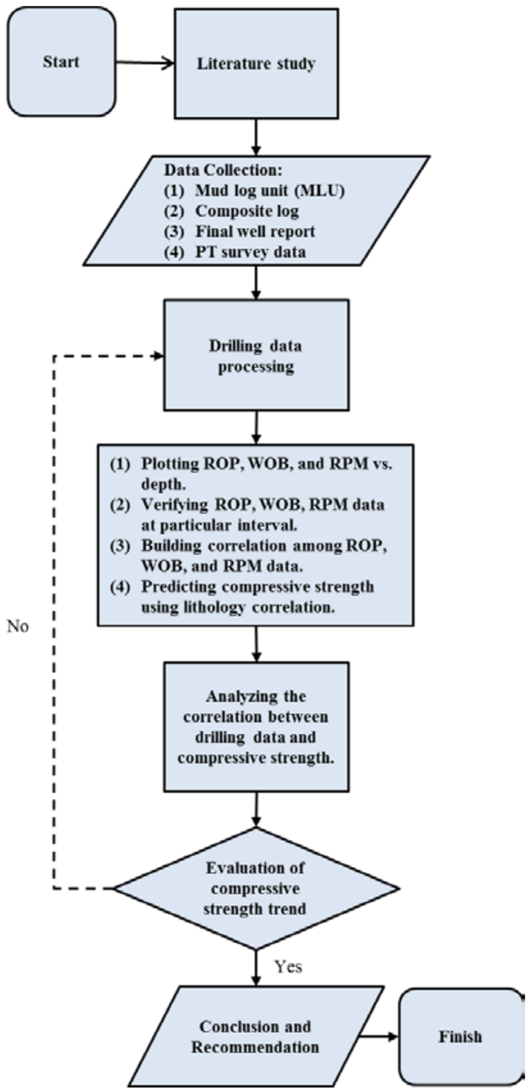


Figure 1: Study Methodology

3. BASIC THEORY

3.1. Geothermal Rocks Characteristics

Geothermal fields in Indonesia that located in volcanic area tend to be dominated by igneous and metamorphic rocks. Igneous rock is formed by magma cooling and crystallized with earth's crust material. Geothermal rock types are often found including rhyolite, andesite, basalt, and tuff. These rocks can be also distinguished by their physical and mechanical properties [3].

Several rock physical parameters can be determined from laboratory test and in-situ test, such as:

- **Density**
  Rocks density in volcanic area are generally larger than non-volcanic area. The density value is different at each depth in each formation lithology. Geothermal rocks density such as basaltic andesite lava is approximately 2600-2700 kg/m^3 [8].

- **Porosity**
  Porosity is the ratio between the volume of the pore space and the tested total volume rock samples. Typical geothermal rock samples porosity such as lava andesite, breccia andesite, lava rhyolite, and breccia rhyolite shown in **Figure 2.** The result shows that porosity of geothermal rock is about 20-40%[6].

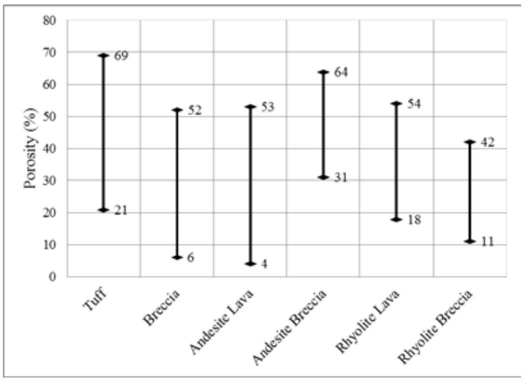


Figure 2: Rock porosity from laboratory test [6]

- **Permeability**
  Permeability provides information about the connectivity of pore space and fracture within the rocks. It is also defined as the rock ability to flow fluids. Typical geothermal rock samples permeability such as lava andesite, breccia andesite, lava rhyolite, and breccia rhyolite shown in **Figure 3.** The result shows that permeability of geothermal rock is about 0-1.8 mDarcy [6].

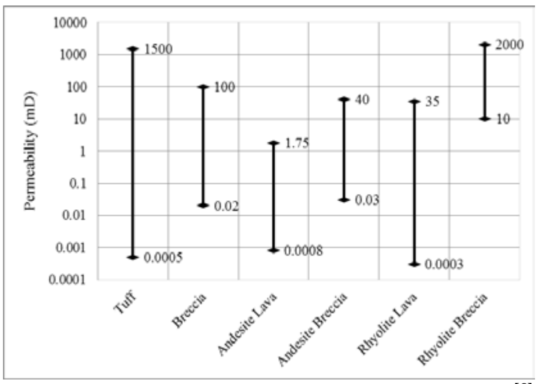


Figure 3: Rock permeability from laboratory test [6]

- **Rock strength**
  Rock strength index test in **Figure 4** is obtained from laboratory test. Based on Hoek & Brown[4] classification, the geothermal rock compressive strength value such as rhyolite and tuff has very strong rock compressive strength approximately about 100-250 MPa.

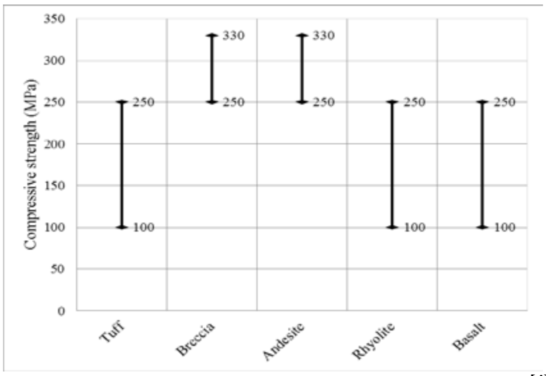


Figure 4: Rock strength index from laboratory -test [4]

- **Rock physical properties and compressive strength relationships**
  Physical rock properties such as porosity and permeability will affect geothermal rock compressive strength magnitude. Generally, as the porosity and permeability get greater value, the rock compressive strength magnitude gets less and vice versa. As an example, compressive strength of breccia rock on **Figure 4** is greater than any other rock because it has a very low porosity (5-30%) and permeability (0.01-1 mD).

3.2. Drilling Geomechanics Principle

Geomechanics is the theoretical and applied science of the mechanical behavior of rock related to the force fields of its physical environment. In geomechanics principle, stress condition is the most important parameter to be analyzed. The stress conditions are divided into in-situ stress and wellbore stress. In-situ stress is defined as a stress condition before the well being drilled and the stress in equilibrium state [1].

3.2.1. Rock strength variable

In-situ stress determination is influenced by several rock strength variable. In geomechanics, rock strength were [1]:

1. Uniaxial compressive strength (UCS)
2. Poisson's ratio (ν)
3. Young's modulus (E)
4. Cohesion (S_o)
5. Friction sliding angle (Ø)

Some of rock strength parameter magnitudes are affected by wellbore lithology characteristics. The geothermal rock strength should be accessed accurately because it has a different values in each section of the formation. Technically, knowledge about rock strength distribution inside the wellbore will be help drilling engineers making decision in designing future development well.

3.2.2. Uniaxial compressive strength (UCS)

Rock strength parameter can be measured directly using rock mechanic test both either in rig site or laboratory. Rock compressive strength measurement can be done indirectly using drilling data or well logging. Indirect method of rock compressive strength measurement is relatively simple and fast because of not using rock sample.

The use of drilling data to predict the rock compressive strength has been developed in a long time for many types of drill bit used. Rock compressive strength value measurement in this study contains following variable such as operating condition for geothermal drilling is influenced by following parameter:

1. Geothermal rock lithology
2. Formation temperature and pressure
3. Mud and drilling hydraulic

4. CASE STUDY

Well X is an exploration well which is located in Indonesia. Well X reaches 2,142.51 mMD. The drilling purpose of the Well X is to get subsurface data and to prove geothermal potential.

4.1. Pressure and temperature data

Well X pressure and temperature survey was conducted. From the survey, it informs that the reservoir temperature is about 260ºC and the reservoir fluid characteristic is compressed liquid. The results of the pressure and temperature survey is shown in **Figure 5.**

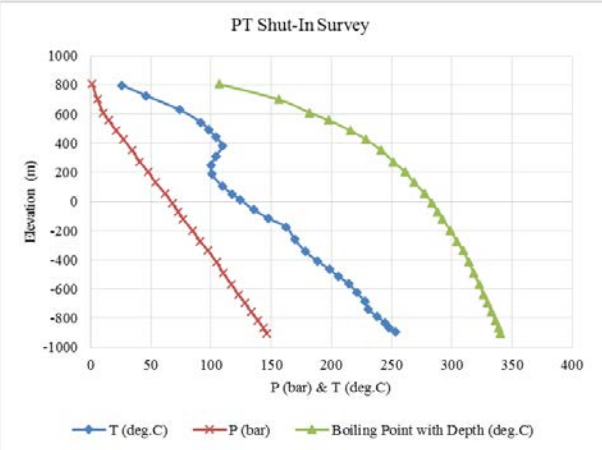


Figure 5: Pressure and Temperature Survey Results [2]

4.2. Well lithology data

Geothermal well lithology can be constructed from the drilling composite log data. Macroscopic analysis result from the cutting samples obtained from geothermal Well X on depth ranging from 36 mMD to 930 mMD. **Table 1** shows that geothermal The formation are composed by: a combination of andesite breccia, altered tuff breccia, altered tuff, altered andesite breccia, altered andesite, altered basaltic andesite.

Table 1: Geothermal Well X lithology

Hole Section	Depth (m)	Lithology	Hardness
26"	36-60	Volcanic Mat.	Soft-Hard
	60-74	Breccia Andesite	Medium-Hard
	75-115	Alt. Breccia Tuff	Soft-Medium
	115-143	Alt. Tuff	Soft-Medium
17 1/2"	143-155	Alt. Breccia Andesite	Medium-Hard
	155-165	Alt. Andesite	Soft-Medium
	165-200	Alt. Breccia Tuff	Medium-Hard
	209-239	Alt. Andesite (Basaltic)	Soft-Medium
	239-248	Alt. Breccia Tuff	Soft-Medium
	248-257	Alt. Breccia Andesite	Medium-Hard
	257-288	Alt. Andesite (Basaltic)	Soft-Medium
	288-302	Alt. Breccia Andesite	Medium-Hard
	302-320	Alt. Andesite	Hard
	320-359	Alt. Andesite (Basaltic)	Hard
	359-404	Alt. Breccia Andesite	Soft-Hard
12 1/4"	431-443	Alt. Andesite	Hard
	443-462		
	443-462	Alt. Andesite	Hard
	512-557	Alt. Andesite (Basaltic)	Hard
	557-596		
	596-655		
	655-737	Alt. Breccia Andesite	Medium-Hard
	737-743	Alt. Andesite (Basaltic)	Soft-Medium
	743-909	Alt. Breccia Andesite	Soft
	909-930		

4.3. Mud logging data

The mud properties data that used at interval 36-930 mMD shown in **Table 2**.

Table 2: Mud Data

Drilling Fluid Type	Depth Interval (m)	Mud Weight (ppg)	Plastic Viscosity (cp)	Yield Point (lb/100ft^2)
Water Based Mud Gel Water	36-480	8.58-8.83	12-24	13-23
Water Based Mud Gel Water	480-500	8.58-8.83	24	23
Water Based Mud Gel Water	500-930	8.58-8.83	12-24	13-23

4.4. Bit and BHA data

Bit life and bit performance are affected by: lithology and drilling parameter such as rotary speed (RPM), Weight on Bit (WOB), hydraulics, etc[5]. In this study, bit analysis is conducted in geothermal water dominated wells. The bit size and data of the BHA which are used at interval 36-930 mMD are shown in **Table 3**.

Table 3: Bit & BHA data summary in geothermal Well X

New Bit #1		
Depth interval (m)	36.0 – 145.0	
Bit hours (hrs)	12.9	
Average ROP (min/m)	6.40	
BHA Assembly	26" Rock bit 9 5/8” Mud Motor 9 3/4" Shock Sub 9" Float Sub 26" String STB 9.5" DC 26" String STB	9.5" DC x/o Sub 8" JARS 8" DC x/o Sub 5" HWDP
Weight on Bit (ton)	2 – 3	
New Bit #2		
Depth interval (m)	145.0 – 310.0	
Bit hours (hrs)	48.0	
Average ROP (min/m)	17.45	
BHA Assembly	17-1/2" Rock bit 9-5/8" Motor 9-13/16" Shock Sub 9 Float Sub x/o Sub 17-1/2" String Stab 1 x 8" DC	17-1/2" String Stab 3 x 8"DC 8" Jars 1 x 8" DC x/o Sub 5" HWDP
Weight on Bit (ton)	1– 10	
New Bit #3		
Depth interval (m)	310.0 – 413.0	
Bit hours (hrs)	51.8	
Average ROP (min/m)	25.69	
BHA Assembly	17-1/2" Rock bit 9-5/8" Motor 9-13/16" Shock Sub 9 Float Sub x/o Sub 17-1/2" String Stab 1 x 8" DC	17-1/2" String Stab 3 x 8"DC 8" Jars 1 x 8" DC x/o Sub 5" HWDP
Weight on Bit (ton)	2 - 9	
New Bit #4		
Depth interval (m)	431.0 – 492.0	
Bit hours (hrs)	53.6	
Average ROP (min/m)	52.72	
BHA Assembly	12¼” Hycalog bit 7-3/4” Steerable Motor Float sub w/ Float 8” String Stab Pony Monel MWD Landing sub	NMDC 1 x 8” DC X/O 5” HWDP 7 1/8 “ Jars
Weight on Bit (ton)	1 – 5	
New Bit #5		
Depth interval (m)	492.0 – 500.0	
Bit hours (hrs)	14.9	
Average ROP (min/m)	111.75	
BHA Assembly	12¼" Hycalog bit 7-3/4" Steerable Motor Float sub w/ Float 8" String Stab Pony Monel	NMDC 1 x 8" DC X/O 5" HWDP 7 1/8 " Jars 5" HWDP # 7

	MWD Landing sub	
Weight on Bit (ton)	2 – 6	
Re-Run #6		
Depth interval (m)	500.0 – 546.0	
Bit hours (hrs)	54.5	
Average ROP (min/m)	71.09	
BHA Assembly	12¼" Hycalog bit 7¾" Steerable motor Float sub w/float String stabilizer Pony monel MWD Landing sub	Non-magnetic collar 1x8" Drill collar X/O 5" HWDP 7⅛ Jars
Weight on Bit (ton)	4 – 7	
New Bit #7		
Depth interval (m)	546.0 – 764.0	
Bit hours (hrs)	59.6	
Average ROP (min/m)	16.40	
BHA Assembly	12¼" Hycalog bit 7¾" Steerable motor Float sub w/float String stabilizer Pony monel	MWD Landing sub Non magnetic collar 1x8" Drill collar X/O 7⅛ Jars
Weight on Bit (ton)	3 – 10	
New Bit #8		
Depth interval (m)	764.0 – 930.0	
Bit hours (hrs)	11.1	
Average ROP (min/m)	4.01	
BHA Assembly	8½" Rock Bit/Varel	8½" String Stab
	8½" Near Bit Stab 6½" Float sub w/float 6½" Landing Sub 6½" NMDC	6½" Drillcollar 5" HWDP 6½" Jars
Weight on Bit (ton)	3 – 10	

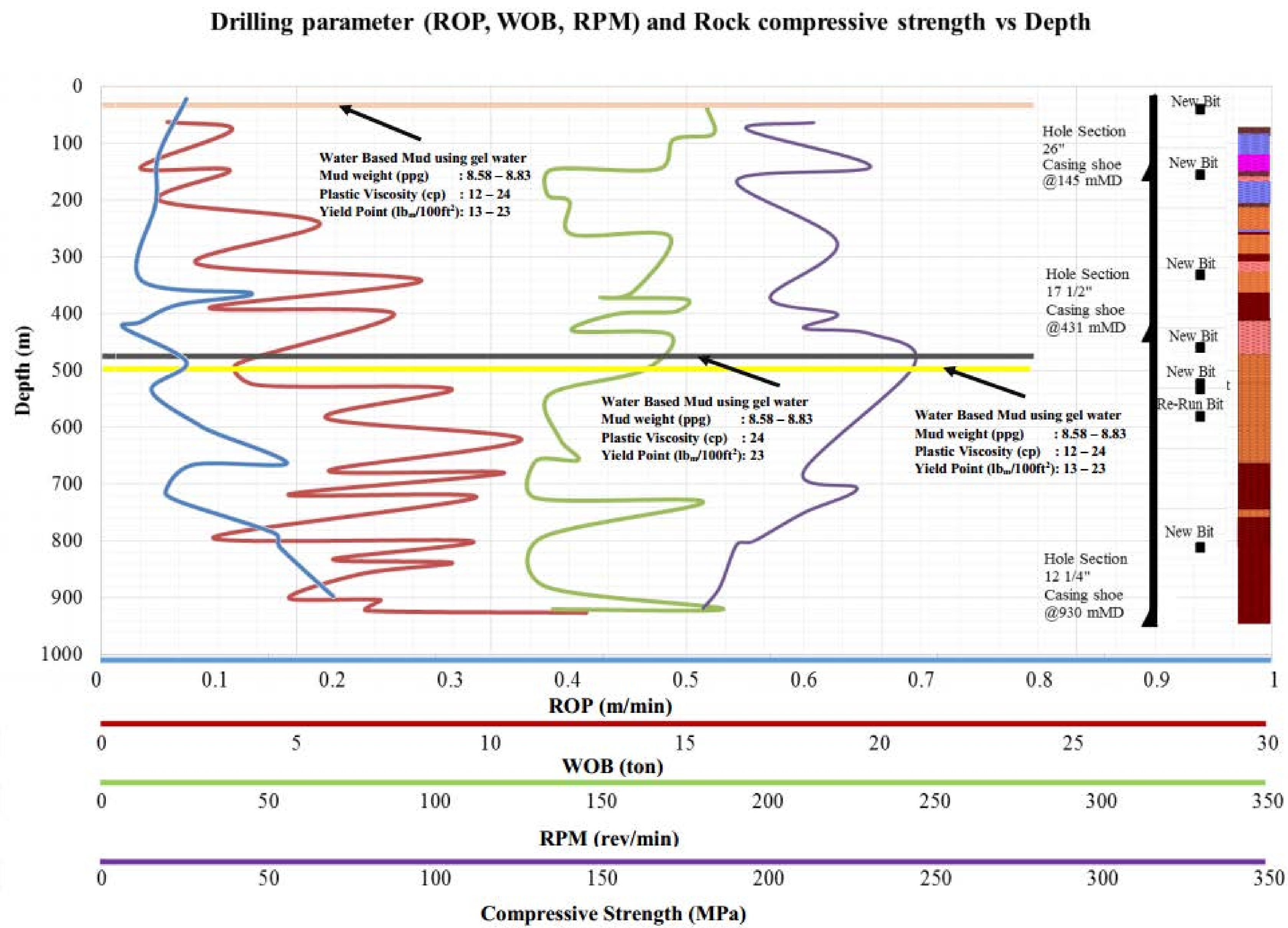
4.6. Well problem data

During drilling operation, there are several problems that were observed and found from final well report such as loss circulation problems and mechanical problems. However, the mechanical problems that are occurred during the drilling operation is negligible as it is not affect the geomechanic aspect.

4.6.1. Loss circulation zone

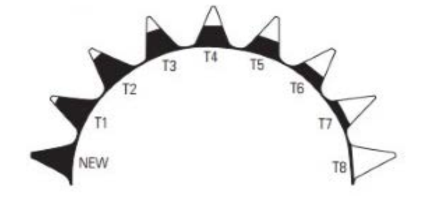
Loss circulation is the common problem encountered in geothermal drilling. This zone can negatively affect the drilling operation if it is not found at productive reservoir zone. The analysis performed by identifying final Well X drilling report. There are several partial loss circulation (PLC) zone in Well X, such as:

1. PLC at depth 692-695 mMD, loss rate 0.67 bpm
2. PLC at depth 843 mMD, loss rate 0.5-2 bpm
3. PLC at depth 858 mMD, loss rate 0.5-1 bpm
4. PLC at depth 880-899 mMD, loss rate 0.5-1.5 bpm



Remarks	Interval (m)	Bit Dullness After Operation
New Bit #1	36-145	T1 B1 G1
New Bit #2	145-310	T1 B3 G2
New Bit #3	310-431	T1 B3 G2
New Bit #4	431-492	T3 B3 G1
New Bit #5	492-500	N/A
Re-Run #6	500-546	T2 B3 G1
New Bit #7	546-764	T2 B3 G1
New Bit #8	764-930	T1 B1 G1

Legend	Remarks
T	Cutting stucture



Legend	Remarks
B	Bearing/seals
B = 0	No life used
B = 8	All life used
G	Gauge
G = 1	Undergauged increament of 1/16 in
G = 8	Undergauged increament of 8/16 in

Legend:	
	Alt. Andesite
	Breccia Andesite
	Alt. Tuff
	Alt. Breccia Andesite
	Alt. Breccia Tuff
	Alt. Andesite Breccia

Figure 6: Drilling parameter and rock compressive strength trend correlation at 36-930 m depth

Table 5: Drilling parameter and geothermal rock compressive strength trend analysis on 36-930 m interval

Depth (m)	ROP	WOB	RPM	Lithology hardness	Compressive strength trend prediction
60-90	Increase	Decrease	Decrease	Soft – Medium	Decrease
140-150	Decrease	Increase	Decrease	Medium – Hard	Increase
190-210	Decrease	Decrease	Increase	Soft – Medium	Increase
250-260	Decrease	Decrease	Increase	Medium – Hard	Increase
310-330	Decrease	Increase	Decrease	Hard	Increase
370-400	Decrease	Decrease	Increase	Soft – Hard	Increase
430-440	Decrease	Decrease	Increase	Hard	Increase
530-540	Decrease	Increase	Decrease	Hard	Increase
650-660	Increase	Decrease	Decrease	Hard	Decrease
670-680	Decrease	Increase	Decrease	Medium – Hard	Increase
720-730	Decrease	Increase	Decrease	Medium – Hard	Increase
820-830	Increase	Decrease	Increase	Soft	Decrease
835-840	Increase	Increase	Decrease	Soft	Decrease
900-910	Increase	Increase	Increase	Soft	Decrease

Table 6: Bit performance evaluation

Bit changes	Bit size	Depth interval (m)	Footage drilled (m)	Bit hour (hrs.)	Bit Dullness After Operation
New Bit #1	26"	36 – 145	109	12.9	T1 B1 G1
New Bit #2	17-1/2"	145 – 310	165	48.0	T1 B3 G2
New Bit #3	17-1/2"	310 – 431	121	51.8	T1 B3 G2
New Bit #4	12-1/4"	431 – 492	61	53.6	T1 B3 G1
New Bit #5	12-1/4"	492 – 500	8	14.9	N/A
Re-Run #6	12-1/4"	500 – 546	46	54.5	T2 B3 G1
New Bit #7	12-1/4"	546 – 764	218	59.6	T2 B3 G1
New Bit #8	12-1/4"	764 – 930	166	11.1	T1 B1 G1

5. DATA ANALYSIS

5.1. Drilling parameter vs. depth analysis

Drilling parameters that are used to predict rock compressive strength in this study are Rate of Penetration (ROP), Weight on Bit (WOB), and Revolution per Minute (RPM). This study is done by analyzing each parameter at every depth interval and described by **Table 5.** Based on the drilling parameter data, generally, when the lithology hardness is soft, then the ROP is increasing. WOB and RPM along the depth interval is fluctuated as there is a drilling problem, such as the loss circulation problem.

5.2. Compressive strength vs. drilling parameter analysis

One of the most important factor that influenced the geothermal rock compressive strength value is rock lithology. Composite log data from Well X can provides the rock lithology information. Predicted rock compressive strength value is obtained from the drilling parameters. The value of rock compressive strength can be determined through its physical properties of rock lithology and the drilling parameters. The compressive strength prediction is also made by the bit performance which is discussed in 5.3. Based on **Table 5**, the compressive strength has trend:

- Increase:
  Generally, the compressive strength trend is increase when:
  - ROP is decrease, WOB is increase, RPM is decrease, and the lithology hardness is medium to hard.
  - ROP is decrease, WOB is decrease, RPM is increase, and the lithology hardness is soft to medium.
- Decrease:
  Generally, the compressive strength trend is decrease when:
  - ROP is increase, WOB is decrease, RPM is decrease, and the lithology hardness is soft to hard.
  - ROP is increase, WOB is decrease, RPM is increase, and the lithology hardness is soft.
  - ROP is increase, WOB is increase, RPM is decrease, and the lithology hardness is soft.
  - ROP, WOB, RPM is increase, and the lithology hardness is soft.

5.3. Bit evaluation

In this study, the bit performance is evaluated from the footage drilled, bit hour, and the bit dullness after the drilling operation and shows in **Table 6**. The rock compressive strength analysis should be taken when the bit is in good condition. In this study, the bit condition is assumed in the good condition as the bit dullness shows that the bit has maximum dullness criterion at T2, which is still in a good condition.

Based on the footage drilled and the bit hour, it can also give the description of the rock compressive strength. When the footage drilled is not significant as the drilling time is increasing, then it can be concluded that the compressive strength is predicted to be increased.

5.4. Discussion

Drilling information by mud log unit must be processed before plotting to depth. The method used is sorting the drilling parameters such as: ROP, WOB, and RPM for each interval in order to conduct better analysis. The trend of the plotted drilling data is analyzed to find the correlation between drilling information and rock compressive strength.

The result is, high rock compressive strength will affect several parameters such as: the ROP tend to decrease, WOB tend to increase, RPM tend to decrease, and vice versa. But, the value of above parameters does not depend on the trend only. It is also affected by correction due to bit condition, lost circulation zone, mud used in certain interval, and etc.

6. CONCLUSION

The analysis performed to predict geothermal rocks compressive strength using drilling data can be concluded:

1. Drilling data plot cannot be directly correlated but the data should be filtered in order to predict the compressive strength accurately.
2. Drilling data such as ROP, WOB, and RPM have the correlation with rock compressive strength in geothermal wells. While the rock compressive strength increase, the trend of ROP decrease, WOB increase, RPM decrease, and vice versa. However, when the drilling parameter values are found to be fluctuated, it is influenced by drilling fluid used, rock physical properties, loss zone and rock compressive strength that not equal at the same lithology.
3. Bit performance is one of the important factor that affects the compressive strength value.

7. RECOMMENDATION

Rock compressive strength calculations performed in this study should be improve to result the more accurate compressive strength value to be applied in geothermal wells.

The recommendations are:

1. An analytical model by using drilling parameter affected rock compressive strength such as penetration rate (ROP), weight on bit (WOB), rotary speed (RPM), and jet impact force with particular rock types is needed to be created.
2. Further analysis for the bit performance, especially the bit condition as it affects the value of the compressive strength.
3. The rock compressive strength using numerical analysis simulation is needed and it should be compared with the analytical measurement results in order to get an accurate prediction of the rock compressive strength value.

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