EXPERIMENTAL AND SIMULATION STUDIES ON OPTIMUM HYDRAULICS CONDITIONS IN LONG EXTENDED-REACH GEOTHERMAL WELL DRILLING

Shigemi Naganawa[1] and Takashi Okabe[2]

[1]The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

[2]Geothermal Energy Research & Development Co., Ltd., 1-22-4, Shinkawa, Chuo-ku, Tokyo 104-0033, Japan

naganawa@frcer.t.u-tokyo.ac.jp

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ABSTRACT

An ongoing geothermal R&D project in Japan aims to develop an environment-friendly, low-cost, extended-reach drilling technology that enables access to geothermal resources from outside the national parks where they occur. Drilling long, tangential sections using low-density drilling fluid in extended-reach geothermal wells with subnormal pressure and lost circulation zones is challenging. Implementation of both effective cuttings transport and maintenance of an appropriate equivalent circulating density (ECD) in geothermal wells is contradictory and much more difficult than in oil and gas wells.

We conducted a number of experiments to optimize the drilling hydraulics in highly inclined geothermal wells using a large-scale flow-loop apparatus. Optimum hydraulics conditions were obtained in terms of both hole cleaning and ECD management. To evaluate the experimentally obtained optimum conditions at field scale, we conducted numerical simulations on the drilling hydraulics for a long, extended-reach model well. Recommendations for preventing drilling problems such as poor hole cleaning, high torque and drag, stuck pipes, borehole instability and lost circulation are presented.

1. INTRODUCTION

After the United States and Indonesia, Japan has the largest number of geothermal resources in the world (Stefansson, 2005; Bertani, 2010). However, approximately 80% of these geothermal resources are located in natural parks. Therefore, their development has been restricted for years by environmental conservation policies. After the earthquake and the ensuing accident at the Fukushima nuclear power plant on March 11, 2011, geothermal energy was again recognized as a promising renewable energy. Recently, the Japanese government eased regulations to allow geothermal resource development from outside the parks through extended-reach wells.

Under these circumstances, an R&D project on geothermal well drilling technology funded by the Ministry of the Environment was started and is now progressing in Japan (Okabe et al., 2013). This project aims to develop an environment-friendly, low-cost, extended-reach drilling technology to access the geothermal resources located in the national parks. The target horizontal reach is 2,500 m for wells of total depth 3,000 m. Historically, most geothermal wells were vertically or near-vertically drilled. Although extended-reach drilling is now popular in oil and gas development, extended-reach geothermal wells with horizontal departure over 2,500 m have not yet been drilled (Glynn-Morris et al., 2009). If the cost of extended-reach drilling can be reduced by 10%, the total cost of power generation will be lower than that for conventional geothermal development using 2,000 m class vertical or near-vertical wells. Extended-reach drilling also has the advantage of increased steam production rates because of greater penetration of high-temperature hydrothermal reservoirs.

One of the key issues in drilling extended-reach wells is the drilling hydraulics design. Particularly in geothermal wells, drilling long, tangential sections with subnormal pressure and lost circulation zones is challenging because low-density, low-viscosity drilling fluids are usually used to avoid the degradation and gelation of the drilling fluid due to high temperature. Furthermore, to reduce cost, water is often used as the drilling fluid in severe lost circulation zones. Implementation of both effective cuttings transport and maintenance of an appropriate equivalent circulation density (ECD) in geothermal wells is contradictory and much more difficult than in oil and gas wells.

This paper presents a study on mud design and control technique conducted as a part of the above-mentioned R&D project. In this study, we conducted a number of experiments to optimize drilling hydraulics in highly inclined geothermal wells using a large-scale flow-loop apparatus. Optimum hydraulics conditions were obtained in terms of both hole cleaning and ECD management. To evaluate the experimentally obtained optimum conditions at field scale, we conducted numerical simulations for drilling hydraulics for a long, extended-reach model well.

2. EXPERIMENT

2.1 Experimental apparatus

The experimental apparatus used was a large-scale flow-loop apparatus, henceforth referred to as the Cuttings Transport Flow-Loop System (CTFLS). Flow diagram and photograph of the apparatus are shown in Figures 1 and 2, respectively. CTFLS has a 9-m long test section simulating a borehole annulus that consists of a 5″ I.D. outer pipe (borehole/casing) and a 2.063″ O.D. inner pipe (drill pipe).

This apparatus is a once-through type of flow loop, meaning that drilling conditions with arbitrary penetration rates from 5 to 50 m/h can be reproduced by controlling the feed rate of cuttings into the test section. Cuttings are fed and mixed into the fluid flow line at the inlet (bottomhole side) of the test section by a screw feeder at a given rate. Cuttings discharged from the outlet (surface side) of the test section are separated from the drilling fluid at the shaker screen and conveyed to the reservoir hopper by a bucket conveyer. Weights of the cuttings feed hopper and the reservoir hopper are continuously measured by the respective load cells; this data is used to calculate the weight of the cuttings in the test section annulus. The drilling fluid is diverted to the return tank and subsequently pumped again into the flow loop.

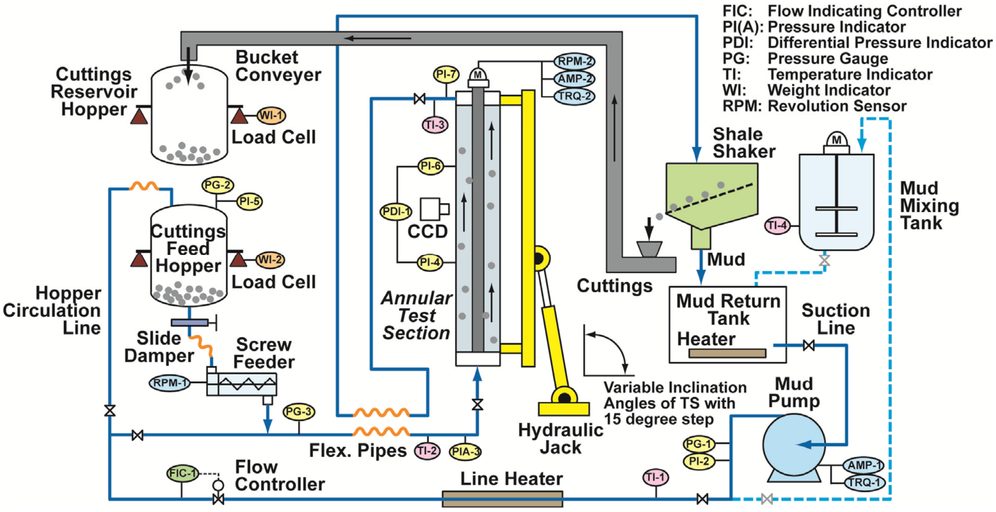


Figure 1: Schematic flow of CTFLS.

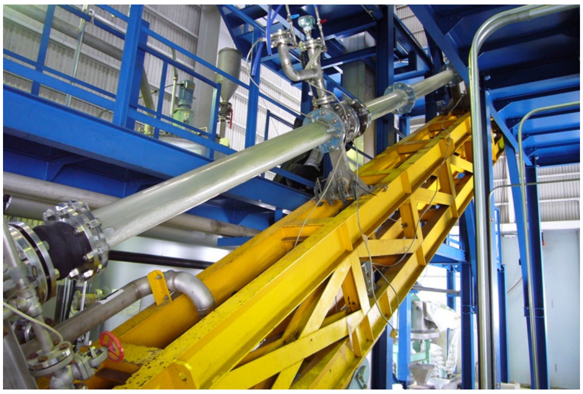


Figure 2: CTFLS.

The inclination angle of the test section can be arbitrarily set between vertical (0°) and horizontal (90°) in 15° steps. The inner pipe can be set either concentric or eccentric to the outer pipe. To enable visual observation of the flow behavior in the annulus, the middle section of the 7-m long outer pipe is composed of transparent acrylic resin. Data from sensors, such as hopper weight, differential pressure, and temperature, are digitized and stored at 1 s intervals in a computer, which can be simultaneously monitored online.

2.2 Experimental method and conditions

In the experiment, fluid flow rates were changed in five equal steps from 70 m^3/h to 30 m^3/h. The cumulative weight of fed and returned cuttings and the frictional pressure loss in the annulus were continuously recorded as time series data. From this time series data, the cuttings volume concentration in the annulus and the frictional pressure loss for each fluid flow rate under steady state condition were obtained. The procedure to obtain this steady state data is described in our previous work (Naganawa, 2013).

The experimental conditions are summarized in Table 1. In this study, experiments were conducted at annulus inclination angles of 0, 30, 45, 60 and 75°. Spherical ceramic balls with density nearly the same as that of typical rock were used as the cuttings. The rate of penetration was set at 10 m/h for all experiments. Two types of drilling fluids were used: "Water" and "Mud 2" which is a bentonite mud: water + 5% bentonite + 0.1% Partially Hydrolyzed Polyacrylamide (PHPA). Mud 2 is composed of simple components and is a typical low-density, low-viscosity drilling fluid used in geothermal drilling. The rheological properties of the drilling fluids are shown in Table 2.

Table 1: Experimental conditions.

Hole I.D.	5″
Drill Pipe O.D.	2.063″
DP Eccentricity	0.8
Hole Inclination	0, 30, 45, 60, 75°
Drilling Fluid	Water
	Mud 2
	(water + 5% bentonite + 0.1% PHPA)
Fluid Density	1.0–1.03 SG
Fluid Temperature	30°C
Fluid Flow Rate	30–70 m^3/h (0.79–1.85 m/s)
Cuttings Diameter	3.2 mm (≈1/8″)
Cuttings Density	2.4 SG
Penetration Rate	10 m/h (0.13 m^3/h)

Table 2: Average properties of drilling fluids.

	Density (SG)	Plastic Viscosity (cp)	Yield Point (lbf/100ft^2)	Initial Gel Strength (lbf/100ft^2)
Water	1.00	1	0	0
Mud 2	1.03	20	14	3

2.3 Experimental results

Experimental results for the cuttings volume concentration in the annulus are shown in Figure 3. For both drilling fluids, the cuttings concentration increased with increase in annulus inclination angle at flow rates below 50 m^3/h. Furthermore, the cuttings concentration at this low fluid flow rate was slightly higher in the Water case than in the Mud 2 case. With an inclination angle greater than 30° in both cases, sufficient hole cleaning could be achieved by maintaining a fluid flow rate greater than 50 m^3/h. The corresponding annular velocity (i.e., average fluid velocity in the annulus) was 1.3 m/s, which is considered to be the minimum flow rate for sufficient cuttings transport in an inclined wellbore.

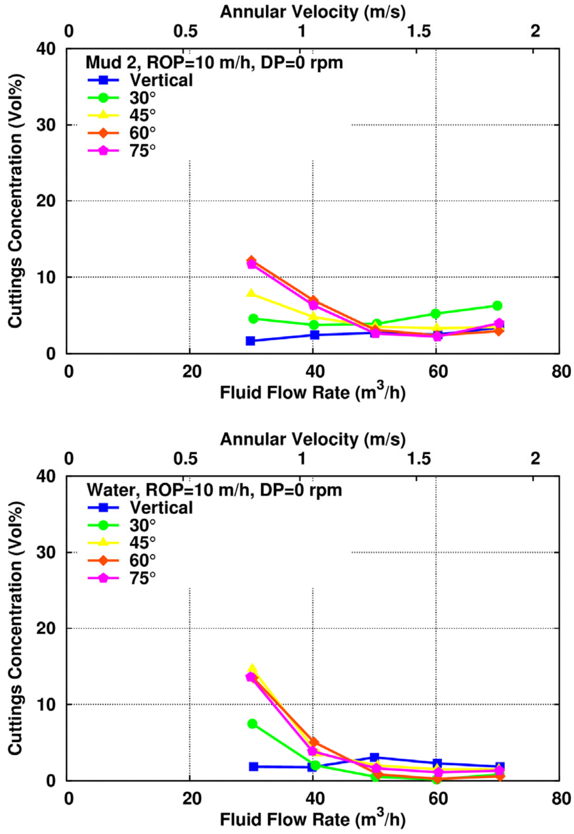


Figure 3: Experimental results for cuttings volume concentration in the annulus.

Experimental results for frictional pressure loss in the annulus are shown in Figure 4. The frictional pressure loss was almost independent of the hole inclination angle at flow rates greater than 40 m^3/h, which also provided sufficient hole cleaning for both fluids. However, the magnitude of the frictional pressure loss for Mud 2 at these high flow rates was more than twice that of Water. On the other hand, the frictional pressure loss increased with the hole inclination angle and increasing cuttings concentration at flow rate range less than 40 m^3/h. In addition, the increase in frictional pressure loss was predominant for the medium range of inclination angles, i.e., around 30–45°, especially with Water. As seen in Figure 3, the difference in cuttings concentration of Water and Mud 2 was not as pronounced as the difference in the frictional pressure loss, indicating that the difference in pressure loss for the medium range of hole inclination angles might arise from factors other than the increase in the cuttings concentration.

Figure 5 shows visual observations of the cuttings transport behavior for Water flow at a hole inclination angle of 45° and a flow rate of 30 m^3/h. The difference in the magnitude of the frictional pressure loss for the medium range of hole inclination angles is considered to depend on the solid–liquid two-phase flow regime. The cuttings were observed to form a disturbed dune, and they dynamically flowed in whirls and gradually moved upward in the 45° case. However, for the 70° case, cuttings were stratified and transported as a slow-moving bed of relatively uniform height.

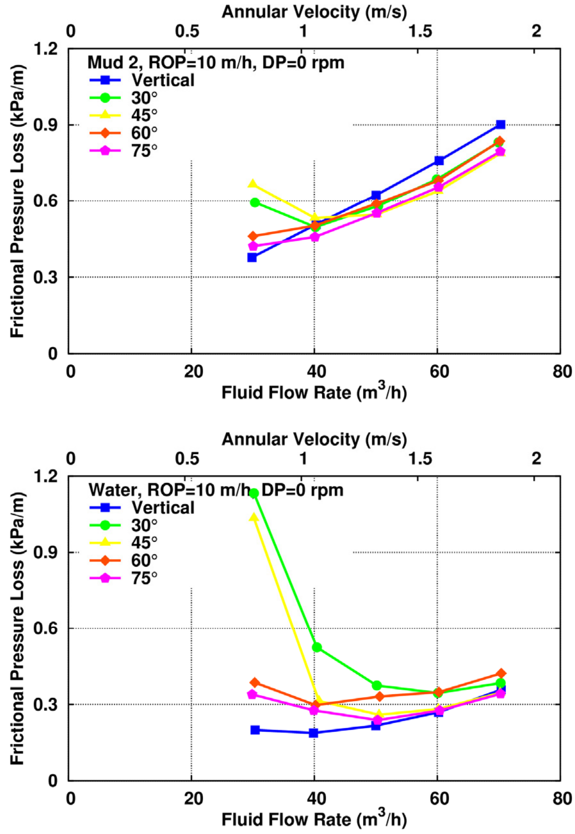


Figure 4: Experimental results for frictional pressure loss.

As mentioned above, we obtained the minimum annular velocity required for sufficient hole cleaning in an inclined well drilling as approximately 1.3 m/s for both Water and Mud 2 cases. However, to avoid lost circulation, the frictional pressure loss in the annulus should be maintained as low as possible considering limited mud pump capacity and appropriate downhole pressure control. Considering this factor, the optimum annular velocities would be 1.0 m/s for Mud 2 and 1.4 m/s for Water, which would ensure minimal frictional pressure loss while allowing some increase in the cuttings concentration in the annulus.

3. FIELD SCALE SIMULATION

3.1 Description of the simulator

The cuttings transport simulator we used was developed through a collaborative research project between the University of Tokyo and the Japan Oil, Gas and Metals National Corporation (JOGMEC). The simulator predicts the transient behaviors of annular pressure, cuttings bed height, suspended cuttings concentration, and phase velocities, along the entire trajectory of the well. The original basic modeling, covering underbalanced operation with aerated mud, was presented in our previous work (Doan et al., 2003), and improvements in its ability to simulate the cuttings transport behavior of extended-reach wells with a complex well trajectory can be found in our other work (Naganawa and Nomura, 2006).

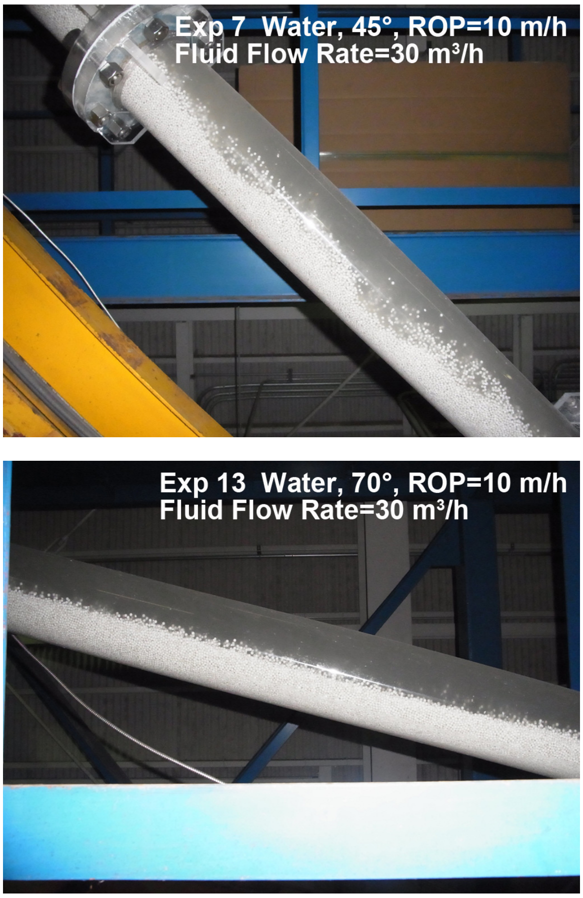


Figure 5: Observed cuttings transport behaviors showing different liquid–solid, two-phase, flow regimes depending on the hole inclination angle.

The mathematical model of the simulator is described as the "Two-Layer model," which deals with transient 1D solid–liquid two-phase flow in the well annulus. The basic equation comprises mass and momentum conservation for each phase in the upper fluid layer and the lower cuttings deposit layer. To close the basic equations mathematically, a couple of constitutive equations were derived considering the cuttings deposition and re-entrainment relationships between the layers. The model parameters in the constitutive equations, such as friction factors, cuttings deposition, and re-entrainment rates, were evaluated and determined by matching the calculated cuttings concentration data with the data obtained from the CTFLS experiments.

The numerical solution method adopted is the Stability-Enhancing Two-Step (SETS) method (Mahaffy, 1982), which eliminates the restriction on the Courant–Friedrichs–Lewy condition that existed in the conventional semi-implicit numerical scheme. The SETS method dramatically improves the computation time because of the possibility of using a larger time step without sacrificing stability.

3.2 Model well and simulation conditions

To evaluate the experimentally obtained optimum conditions at field scale, we conducted numerical simulations on the drilling hydraulics for a long, extended-reach model well. We assumed a model well with total depth 3,000 m, horizontal departure 2,500 m, and maximum hole inclination angle 70°, as shown in Figure 6. To maximize the steam production rate, a 9-5/8″ casing is set at a depth deeper than that for typical oil and gas wells. Therefore, we need to drill a long, tangential section with a larger diameter (12-1/4″) hole and an 8-1/2″ hole, which is conventional in oil and gas wells.

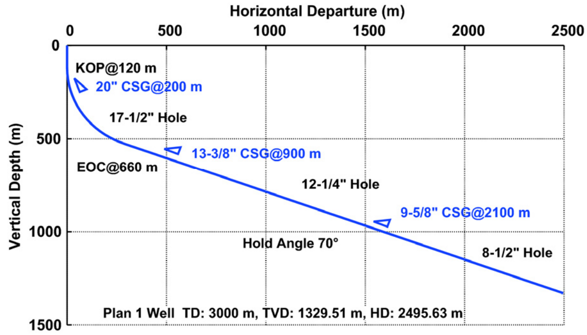


Figure 6: Well trajectory and casing program for the model well.

From these well profiles, we selected two hole sections for simulation targets: (1) 12-1/4″ hole section from 1,830 to 2,100 m MD after setting a 13-3/8″ casing and (2) 8-1/2″ hole section from 2,730 to 3,000 m MD after setting a 9-5/8″ casing. The drilling fluids used in the simulation study were the same as those in the CTFLS experiments, Water and Mud 2. Other simulation conditions are essentially the same as those used in the experiments.

We assumed that the rate of penetration was 9.0 m/h and that 60 min of mud circulation operation for hole cleaning was conducted after drilling one stand of drill pipe (27 m), which is the time required for making a connection with a top drive system. The drill pipe eccentricity was set at 0.0 during circulation operation, but was set at 0.8 during drilling.

3.3 Simulation results for the 8-1/2″ hole section at experimentally obtained optimum mud flow rates

The simulation results for transient behavior of cuttings bed height and ECD distribution during the drilling of the 8-1/2″ hole section with Water and Mud 2 are shown in Figures 7 and 8. The assumed mud flow rates were 380 gpm for Mud 2 and 531 gpm for Water, which are equivalent to the optimum annular velocities obtained from our experiments (1.0 and 1.4 m/s, respectively).

In the Mud 2 case shown in Figure 7, because the experimentally obtained optimum fluid flow rate allows some extent of cuttings deposition to minimize the frictional pressure loss, the simulation results also demonstrated a slightly higher cuttings bed height. In the Water case shown in Figure 8, the cuttings bed height was low and sufficient hole cleaning seemed to be obtained.

In both cases, ECD did not have a constant value along the measured depth and increased with time. As shown in the experimental results, frictional pressure loss in the annulus increased with cuttings deposition, and therefore ECD increased with increasing cuttings deposition over time.

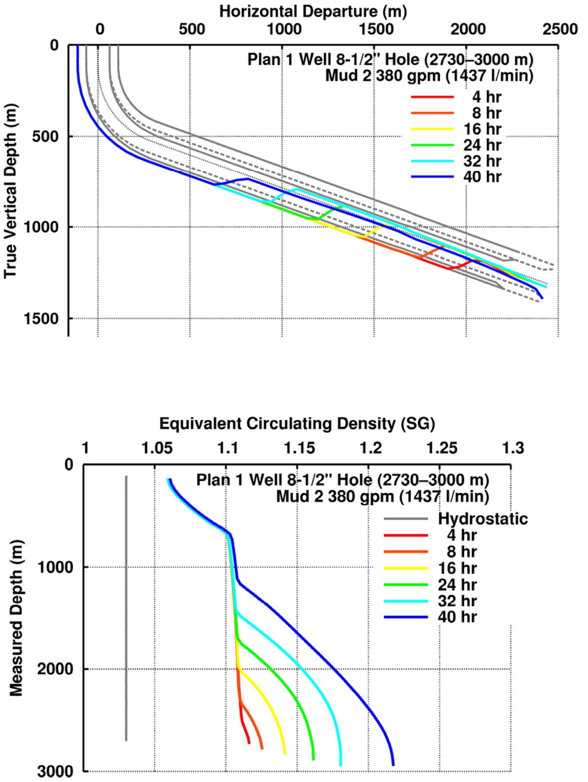


Figure 7: Transient behavior of cuttings bed height and ECD distribution for Mud 2 at the optimum mud flow rate obtained from experiments.

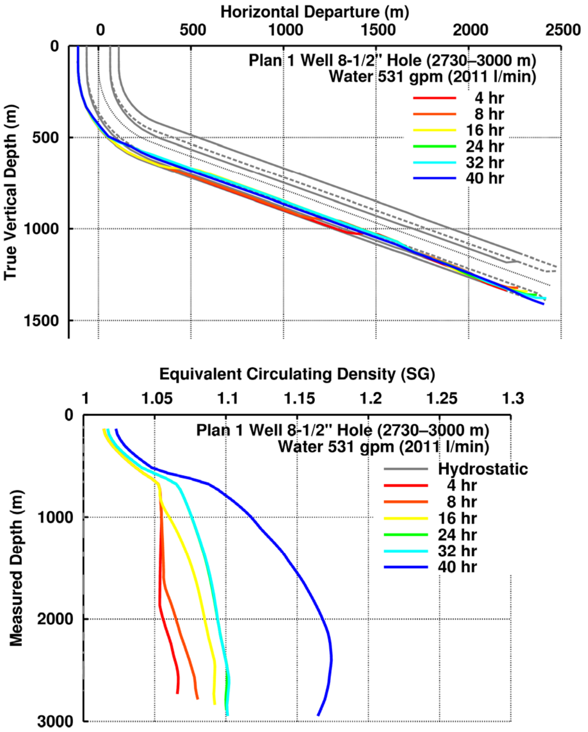


Figure 8: Transient behavior of cuttings bed height and ECD distribution for Water at the optimum mud flow rate obtained from experiments.

In drilling extended-reach wells, formation breakout or lost circulation may not necessarily occur at the casing shoe depth having the lowest formation fracture gradient within the open hole section, which is generally true in vertical wells because ECD increases with measured depth in tangential sections with high inclination angle, as shown in these figures.

4. HYDRAULICS OPTIMIZATION STRATEGY

4.1 8-1/2″ hole section

Here we assume that an 800 hp, 8-1/2″ stroke triplex mud pump system (e.g., NOV 8-P-80 mud pump), typical for 3,000 m class land rig, is used. If we use the smallest 6-1/4″ liners, this mud pump has a maximum circulation rate of 541 gpm. Therefore, the optimum mud flow rates of 380 and 531 gpm used in the previous section can be achieved by a typical mud pump system.

For hydraulics optimization in an 8-1/2″ hole section, simulations at fluid flow rates of 531 gpm and 380 gpm for Mud 2 and Water, respectively, were conducted. As shown in Figure 9, a flow rate of 531 gpm for Mud 2 could reduce the cuttings bed height. However, ECD drastically increased to almost 1.3 SG, which increases the risk of lost circulation. Therefore, the experimentally obtained optimum flow rate for Mud 2 was validated.

On the other hand, in the Water case with a lower flow rate, the cuttings bed height was higher than the optimum flow rate and ECD did not differ much from the optimum flow rate as shown in Figure 10. Conversely, in the Water case, a relatively high fluid flow rate may not greatly increase ECD. Therefore, a sufficient flow rate that can fully suppress cuttings deposition is desirable, and the experimentally obtained optimum fluid flow rate was validated for the Water case also.

Based on these simulation results, if there is a wellbore instability concern, we recommend that a bentonite-based, low-density, low-viscosity drilling fluid such as Mud 2 be used at a relatively low flow rate equivalent to around 1.0 m/s annular velocity. Although this condition allows a relatively high cuttings bed formation, it can avoid excessive ECD increase. On the other hand, if lost circulation is the main concern, we recommend water as the drilling fluid to maintain an ECD much lower than that of the viscous bentonite mud. Water has a cuttings transport capability nearly equal to or in some cases greater than Mud 2.

4.2 12-1/4″ hole section

Generally, due to mud pump capacity, the greater the hole diameter, the smaller the available maximum annular velocity (Sato, 1994). For example, the abovementioned two sets of NOV 8-P-80 mud pumps cannot achieve the optimum flow rate in a 12-1/4″ hole. The maximum achievable mud flow rate is 1,082 gpm and the corresponding annular velocity is about 1.08 m/s.

As a countermeasure for this insufficiency in flow rate, a hole cleaning operation using sweep mud is usually required in oil and gas wells. However, in geothermal well drilling, if we encounter a lost circulation zone, sweep mud would not work as expected (Sakuma et al., 2008). In addition, based on a rule of thumb for extended-reach drilling of oil and gas wells (Mims et al., 2002), conditioning the mud to a high gel strength (or high V-G meter reading at 3 and 6 rpm) may be effective for hole cleaning in a 12-1/4″ hole drilling. However, to achieve cost reduction, we usually use water for drilling total loss zones.

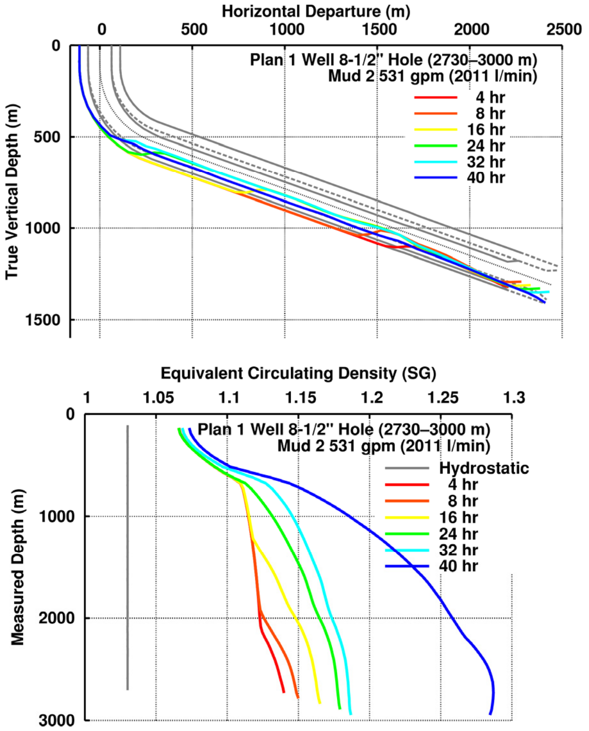


Figure 9: Transient behavior of cuttings bed height and ECD distribution for Mud 2 at higher mud flow rates.

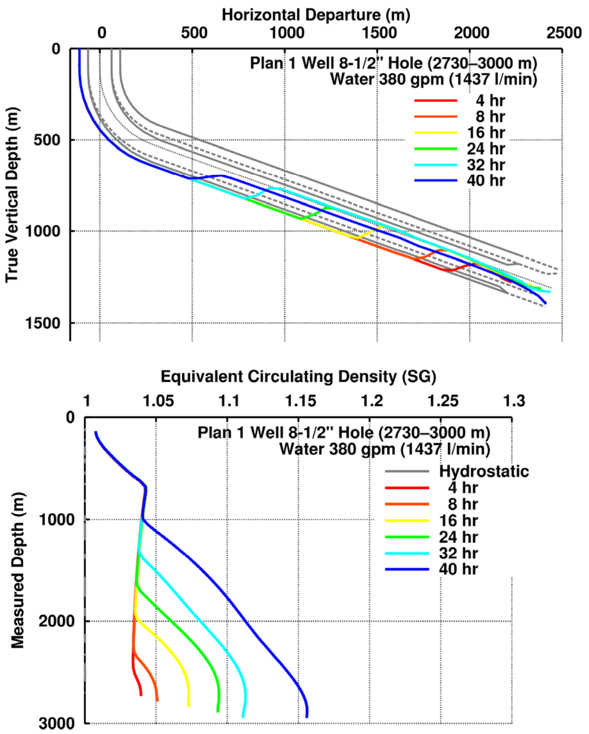


Figure 10: Transient behavior of cuttings bed height and ECD distribution for Water at lower mud flow rates.

To overcome this difficulty, we propose a more frequent mud circulation operation for sufficient hole cleaning. Drill pipe connection is usually made every one stand (three joints, 27 m) when a top drive system is used, and mud circulation for hole cleaning is usually conducted with the same frequency. However, if we conduct a mud circulation operation for hole cleaning every one joint of drill pipe (9 m), better hole cleaning may be achieved. Figure 11 shows the simulation results for drilling a 12-1/4″ hole section at a maximum flow rate of 1,082 gpm with a 60 min mud circulation operation for hole cleaning every one stand, which is the same as in the previous section. In this case, a cuttings bed higher than in the 8-1/2″ hole section was formed.

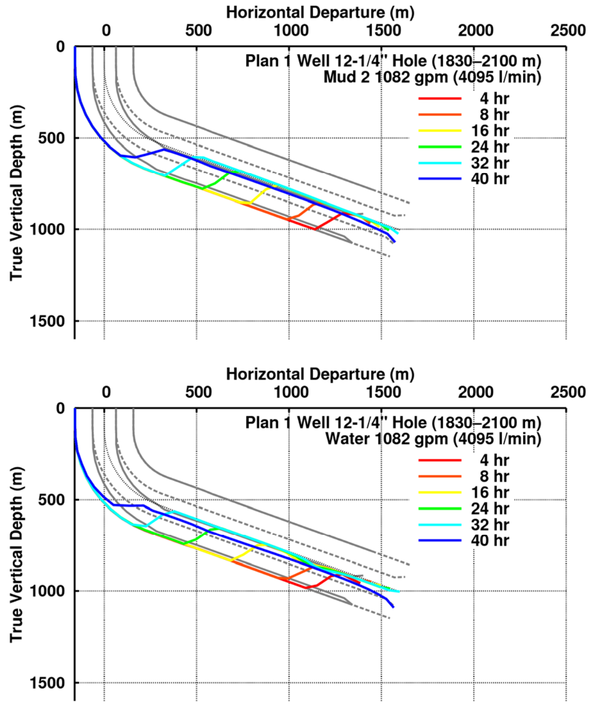
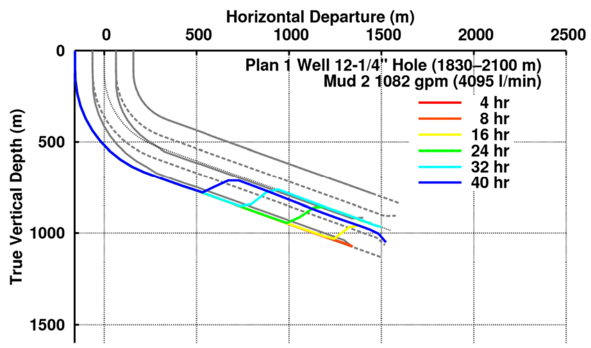


Figure 11: Transient behavior of cuttings bed height for the 12-1/4″ hole section.

The simulation results for drilling a 12-1/4″ hole section at the maximum flow rate of 1,082 gpm with a 20 min mud circulation operation every one joint of drill pipe are shown in Figure 12. The total drilling time is the same as that in Figure 11. Evidently, the cuttings deposition until 16 h was smaller than that in Figure 11.

In drilling a large diameter hole section, if water is used as the drilling fluid with a limited flow rate in a drilling total loss zone and a preferable drilling fluid rheological property for good hole cleaning is not available, more frequent mud circulation is confirmed to be effective for hole cleaning. This operation is considered to be effective for the previously mentioned 8-1/2″ hole section drilling with the Mud 2 bentonite-based fluid also.



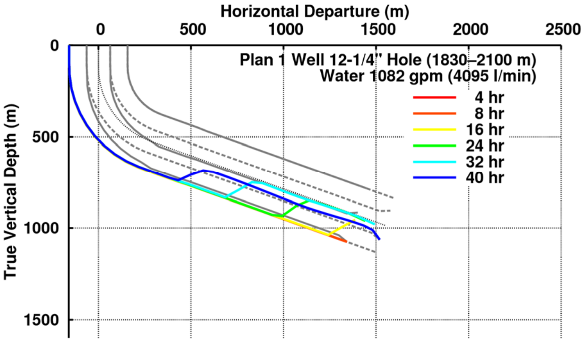


Figure 12: Transient behavior of cuttings bed height for the 12-1/4″ hole section with a more frequent mud circulation operation.

5. CONCLUSION

The recommendations for drilling fluids and hydraulics in drilling long, extended-reach geothermal wells obtained from this study are summarized as follows.

- From the experimental results, the optimum mud flow rate was estimated as the rate that can minimize the frictional pressure loss even with some degree of cuttings deposition in the annulus. The corresponding optimum annular velocities were 1.0 m/s for bentonite mud and 1.4 m/s for water.

- From the simulation study on hydraulics for a 3,000 m total depth and 2,500 m horizontal departure extended-reach geothermal model well, the abovementioned experimentally obtained optimum hydraulics conditions were validated.

- Formation breakout or lost circulation may not necessarily occur at the casing shoe depth generally having the lowest fracture gradient within the open hole section because ECD increases with measured depth in the highly inclined tangential hole section.

- In drilling large diameter hole sections under limited fluid flow rate or when a preferable drilling fluid rheological property for good hole cleaning is not available, a more frequent mud circulation operation for hole cleaning could suppress cuttings deposition in the annulus.

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