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Comprehensive Studies on Hole Cleaning and ECD Management in Long Extended-Reach Geothermal Well Drilling

Shigemi Naganawa and Takashi Okabe

Frontier Research Center for Energy and Resources, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 Japan; Geothermal Energy Research & Development Co., Ltd., 1-22-4 Shinkawa, Chuo-ku, Tokyo 104-0033 Japan

e-mail: naganawa@frcer.t.u-tokyo.ac.jp; okabe@gerd.co.jp

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ABSTRACT

Effective hole cleaning and maintenance of an appropriate equivalent circulating density (ECD) is much more difficult to implement in long extended-reach geothermal wells than in oil and gas wells. We conducted a number of cuttings transport experiments, using a large-scale flow-loop apparatus and field measurements of annular pressure, using PWD (pressure while drilling) in a geothermal directional well recently drilled in Japan. Numerical simulation for the targeted long extended-reach geothermal well with a total depth 3,000 m, horizontal departure of 2,500 m, and maximum hole inclination angle of 70° was performed using a transient hydraulics simulator we developed and modified in this study on the basis of these experiments and field data. In addition, the optimum hydraulics conditions for effective hole cleaning and appropriate ECD management in long extended-reach geothermal drilling are discussed in this study.

1. INTRODUCTION

Geothermal development has been restricted in Japan for many years because approximately 80% of the vast amounts of geothermal resources are located in natural parks. Therefore, a research and development project on geothermal well drilling is under way in Japan that aims to develop an environmentally friendly, low-cost, extended-reach drilling technology enabling access to geothermal resources from outside these natural parks (Okabe et al., 2013).

A key issue in extended-reach drilling is hydraulics design. In geothermal wells with subnormal pressure and lost circulation zones in particular, low-density, low-viscosity drilling fluid or water in some cases is generally used, which is ineffective for acceptable hole cleaning. Although the largest possible flow rate is needed for sufficient hole cleaning with low-density, low-viscosity drilling fluid, and for avoiding an increase of equivalent circulating density (ECD) because of cuttings deposition on the low side of borehole in inclined sections, the excess flow rate can unexpectedly increase ECD, which may cause lost circulation and borehole instability problems. Thus, implementation of an effective hole cleaning method and maintenance of an appropriate ECD are much more difficult to achieve in geothermal wells than in oil and gas wells.

In this study, we conducted a number of cuttings transport experiments, using a large-scale flow-loop apparatus and field measurements of annular pressure using the pressure while drilling (PWD) method in a recently drilled geothermal directional well in Japan. Numerical simulation for the targeted long extended-reach geothermal well with a total depth of 3,000 m, horizontal departure of 2,500 m, and maximum hole inclination angle of 70° degrees was performed using a transient two-layer model hydraulics simulator that we developed and modified on the basis of these experiments and field data. In addition, the optimum hydraulics conditions for effective hole cleaning and appropriate ECD management are discussed, and recommendations are presented for preventing drilling problems such as poor hole cleaning, high torque and drag, stuck pipes, borehole instability, and lost circulation.

2. MODIFICATION OF SIMULATION MODEL PARAMETER USING EXPERIMENTAL AND FIELD DATA

2.1 Description of Simulator

The transient cuttings transport simulator we used in this study was developed through a collaborative research project between the University of Tokyo and 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 parameters, including the process of covering underbalanced operation with aerated mud, was presented in our previous study (Doan et al., 2003), and improvements in its ability to simulate the cuttings transport behavior of extended-reach wells with a complex well trajectory were discussed in another of our studies (Naganawa and Nomura, 2006).

The mathematical model of the simulator is described as the two-layer model, which handles transient 1D solid–liquid two-phase flow in the well annulus, as shown in Figure 1. The basic equation includes mass and momentum conservations for each phase in the upper fluid layer and lower cuttings deposit layer. To close the basic equations mathematically, constitutive equations were derived that consider 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 experiments described in the following section.

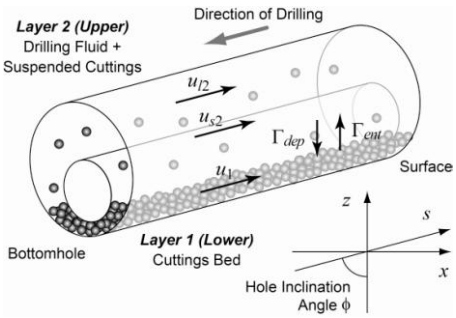


Figure 1: Concept of two-layer model for 1D solid–liquid two-phase flow in annulus.

2.2 Experiments

The experimental apparatus used for simulated model verification was a large-scale flow-loop apparatus referred to as the Cuttings Transport Flow-Loop System (CTFLS). A flow diagram and photograph of the apparatus are shown in Figure 2. The CTFLS has a 9-m long test section simulating a borehole annulus that consists of a 5-in inner diameter outer pipe for the borehole casing and 2.063-in outer diameter inner pipe for the drill pipe. The inclination angle of the test section can be arbitrarily set between vertical (0°) and horizontal (90°) in 15° increments. 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.

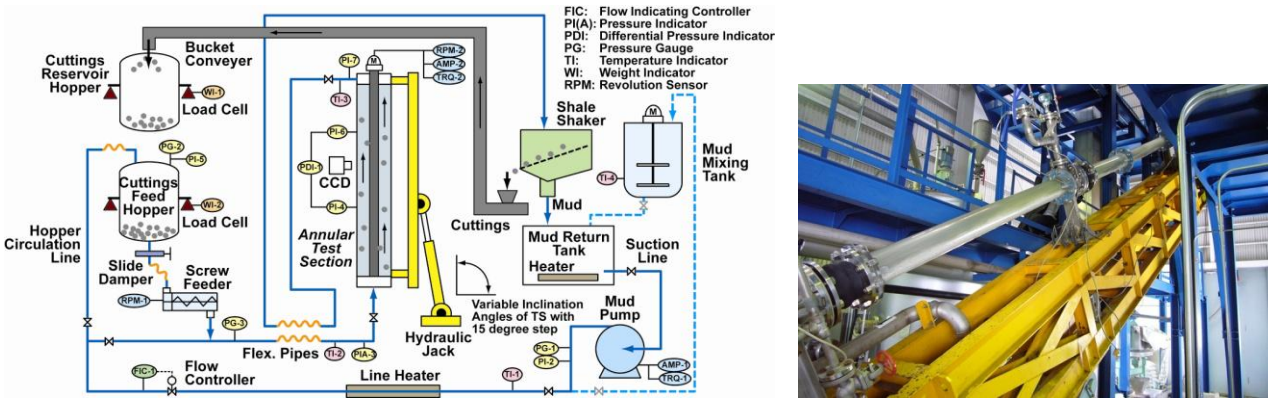


Figure 2: Cuttings Transport Flow-Loop System (CTFLS) experimental apparatus.

This apparatus is a once-through type of flow loop, meaning that drilling conditions with arbitrary penetration rates 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 operating 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 are conveyed to the reservoir hopper by a bucket conveyer. Weights of the cuttings feed hopper and reservoir hopper are continuously measured by the respective load cells; these data are 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. Data from sensors, such as hopper weight, differential pressure, and temperature, are digitized and stored in a computer, which can be simultaneously monitored online.

The experimental conditions are summarized in Table 1. 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 frictional pressure loss in the annulus were continuously recorded as time series data. From this data, the cuttings volume concentration in the annulus and 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 study (Naganawa, 2013).

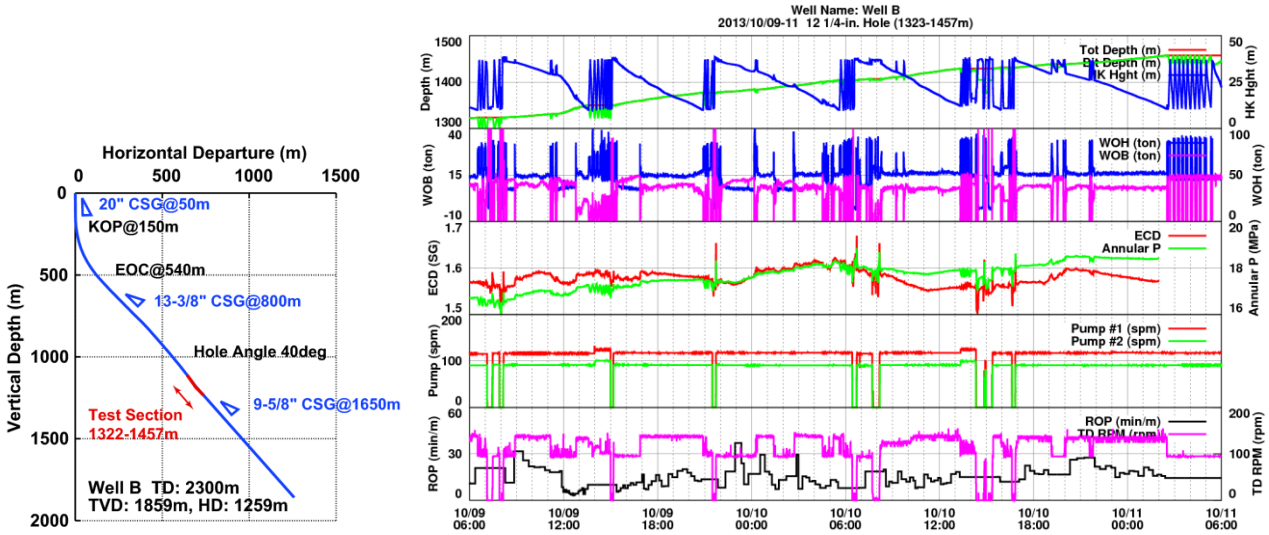
Table 1: Experimental Conditions.

Hole I.D.	5″	
Drill Pipe O.D.	2.063″	
DP Eccentricity	0.8	
Hole Inclination	0, 30, 45, 60, 75°	
Drilling Fluid	Water	PV = 1, YP = 0, Initial Gel = 0
	Mud 2 (water + 5% bentonite + 0.1% PHPA)	PV = 20, YP = 14, Initial Gel = 3
Fluid Density	1.0 SG (Water), 1.03 SG (Mud 2)	
Fluid Temperature	30°C	
Fluid Flow Rate	30–70 m^3/h (0.79–1.85 m/s) in 10 m^3/h steps	
Cuttings Diameter	3.2 mm (≈1/8″)	

Cuttings Density	2.4 SG
Penetration Rate	10 m/h (0.13 m^3/h)

2.3 Annular Pressure Data from Geothermal Exploration Well

Annular pressure data was obtained from a geothermal exploration well (Well B) recently drilled in Japan using the PWD method. As shown in Figure 3, the profile of the well included a total depth (TD) of 2,300 m, total vertical depth (TVD) of 1,859 m, and horizontal departure of 1,259 m. The test section in which PWD data was obtained for this study was a 12–1/4-in hole section of 1,322 m to 1,457 m measured depth (MD) with a maximum hole inclination angle of approximately 40°. The mud logging and PWD data obtained are also shown in Figure 3.



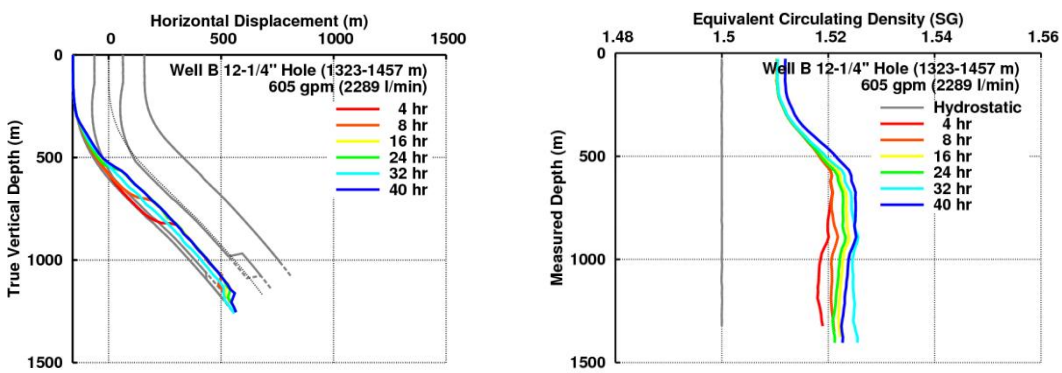
(a) Well profile (b) Mud logging/PWD data

Figure 3: Profile of Well B and obtained mud logging/pressure while drilling (PWD) data.

Unlike the conditions in typical geothermal fields, the formations in which Well B was drilled have relatively high formation pressure, and in some cases abnormal pressure; therefore, the mud weight was maintained at approximately 1.5 SG. The mud rheology was controlled at plastic viscosity (PV) = 19 cp and yield point (YP) = 28 lbf/100ft^2. The operating conditions were selected to maintain a mud flow rate of 605 gpm and an average rate of penetration of 3.17 m/h. During the drilling process in this test section, the rotating mode for a steerable motor was generally used.

2.4 Modification of Friction Factors in the Simulation Model

The results of the preliminary simulation study for the Well B 12–1/4-in hole section by using original simulator we developed are shown in Figure 4. As shown in the figure, that cuttings deposit bed was formed along the tangential section. However, although the measured ECD, using PWD ranged from 1.55 to 1.6 SG, as shown in Figure 3, the maximum simulated ECD was 1.525 SG. Thus, we attempted to modify the friction factors defined in the simulator model as constitutive equations to match the measured and simulated ECDs.



(a) Cuttings bed height (b) Equivalent circulating density (ECD) distribution

Figure 4: Results of preliminary simulation study for Well B using original simulator.

We determined that two types of parameters should be modified. The first includes pipe wall friction factors f_1 and f_2. The original equation of the friction factor was taken from Doron et al. (1987), which is defined as

$$f_1, f_2 = \begin{cases} 16 / Re \\ 0.046 / Re^{0.2} \end{cases}. \tag{1}$$

To compensate the underestimation of ECD for Well B as previously mentioned, we modified the friction factors to be larger than those in the original model:

$$f_1, f_2 = \begin{cases} 16 / Re^{0.86} \\ 0.046 / Re^{0.12} \end{cases}. \tag{2}$$

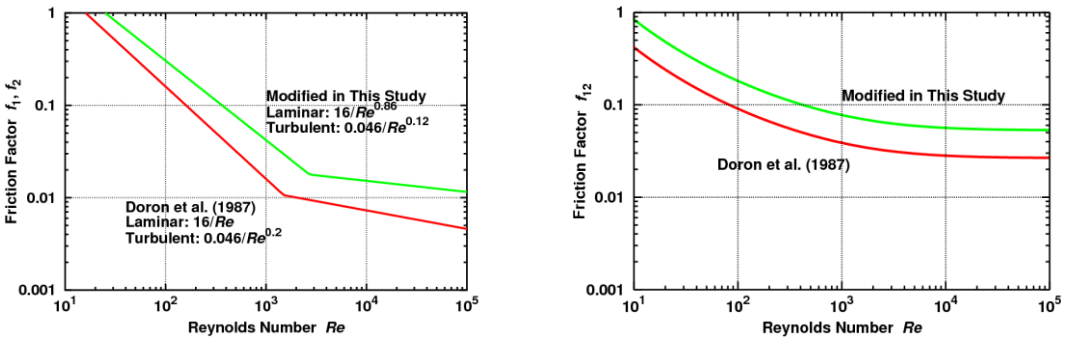
The second parameter to be modified is the friction factor between the upper suspended fluid layer and lower cuttings deposit bed layer, f_{12}. Doron et al. (1987) used the following definition proposed by Televantos et al. (1979), which is half the friction factor for a rough pipe wall surface developed by Colebrook (1939):

$$\frac{1}{\sqrt{2 f_{12}}} = -0.86 \ln\left(\frac{d_p}{3.7 D_2} + \frac{2.51}{Re_{12} \sqrt{2 f_{12}}} \right). \tag{3}$$

The original version of our simulator used the same definition. In the present study, however, we attempted to adopt the original Colebrook equation, defined as follows, to produce a closer match in the cuttings concentration in the annulus:

$$\frac{1}{\sqrt{f_{12}}} = -0.86 \ln\left(\frac{d_p}{3.7 D_2} + \frac{2.51}{Re_{12} \sqrt{f_{12}}} \right). \tag{4}$$

These two friction factor modifications can be graphically demonstrated, as shown in Figure 5.

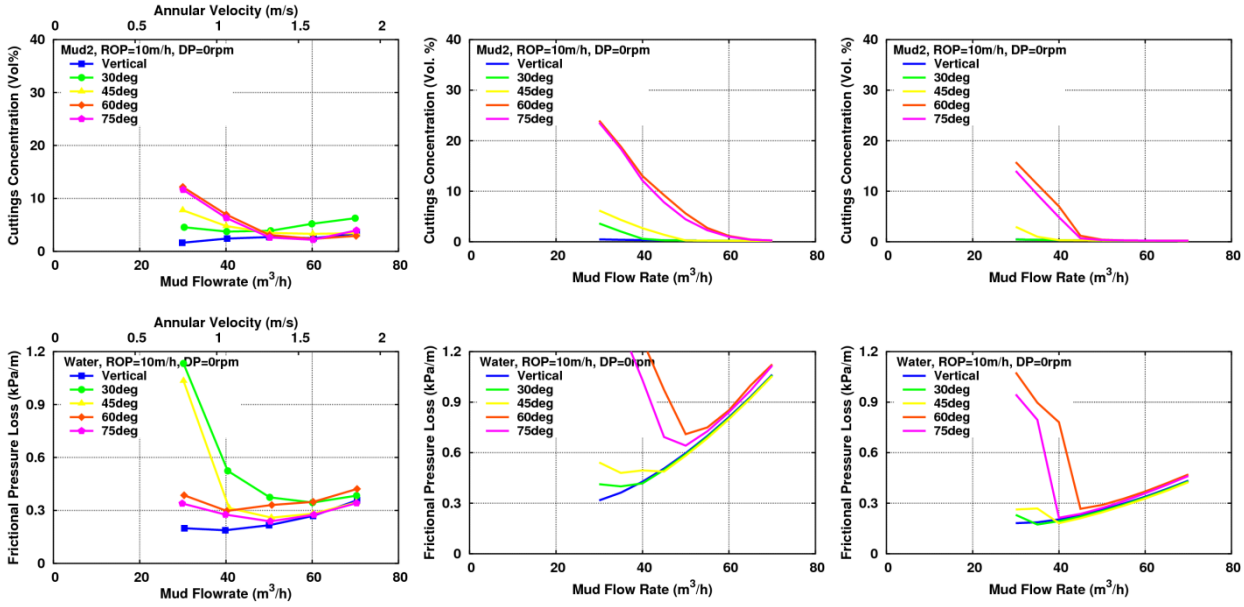


(a) Pipe wall friction factors f_1, f_2

(b) Friction factor between layers f_{12}

Figure 5: Modification of friction factor equations.

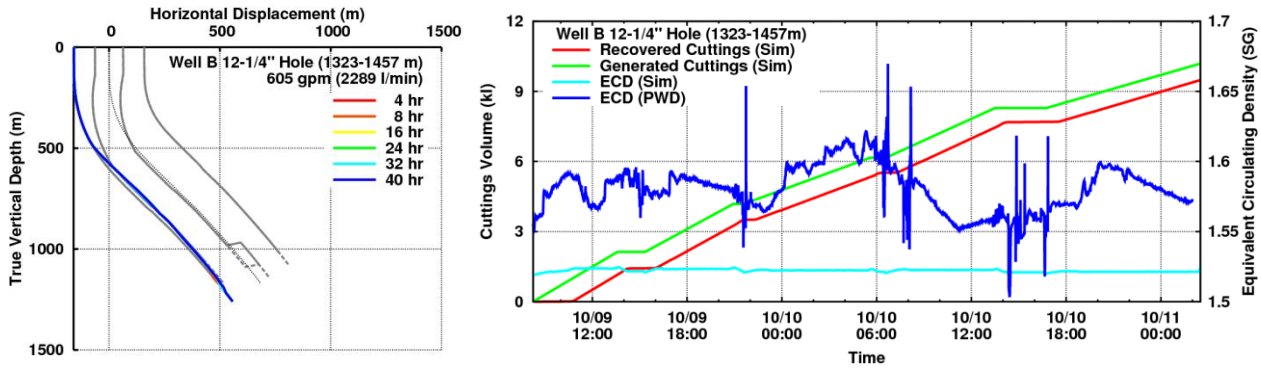
A comparison of steady-state hydraulic behaviors between CTFLS experiments and the simulations is shown in Figure 6. Modification of pipe wall friction factors (center column shown as (b) in the figure) resulted in an overestimation of cuttings concentration in the annulus and frictional pressure loss, compared with the experimental results. Conversely, modification of friction factor between the two layers (right column shown as (c) in the figure) resulted in significantly closer match to the experimental results except for some discrepancy in frictional pressure loss at the lower flow rate region. Although the significant increase in frictional pressure loss for medium-range hole inclination angles of 30° to 45° was observed in the experiments, frictional pressure loss increased to a large extent for hole inclination angles higher than 60° in the simulation. The experimental results may be related to a disturbed dune formed for medium-range hole inclination angles, as reported in our previous study (Naganawa and Okabe, 2013). However, because the simulation used the two-layer model, it could not fully depict such a disturbed dune for such hole inclination angles.



(a) Experimental results (b) f_1, f_2 modification (c) f_{12} modification

Figure 6: Simulation results for Cuttings Transport Flow-Loop System (CTFLS) experimental conditions by using a modified simulator.

The re-simulated result for Well B by using the modified simulator that adopted only f_{12} is shown in Figure 7. The cuttings bed height was simulated as sufficiently low. Presumably, effective hole cleaning was achieved in the actual field. However, ECD estimation by simulation could not determine the actual behavior of ECD obtained by PWD. Therefore, because a limitation may exist in the mathematical model, care must be taken in interpreting the simulation results.



(a) Cuttings bed height (b) Equivalent circulating density (ECD) behavior

Figure 7: Simulation result for Well B by using modified simulator.

3. SIMULATION OF LONG EXTENDED-REACH TARGET WELL

3.1 Model Well and Simulation Conditions

To evaluate the feasibility of good hole cleaning for a long extended-reach geothermal well, we conducted numerical simulation for a model well. We assumed a model well with total depth of 3,000 m, horizontal departure of 2,500 m, and maximum hole inclination angle of 70°, as shown in Figure 8. From these well profiles, we selected two hole sections for simulation targets: (1) a 12–1/4-in section from 1,830 to 2,100 m MD after setting a 13–3/8-in casing and (2) an 8–1/2-in hole section from 2,730 to 3,000 m MD after setting a 9–5/8-in casing.

The drilling fluids used in the simulation study were the same as those used in the CTFLS experiments, which included water and Mud 2 (bentonite mud). Other simulation conditions were 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 and at 0.8 during the drilling process.

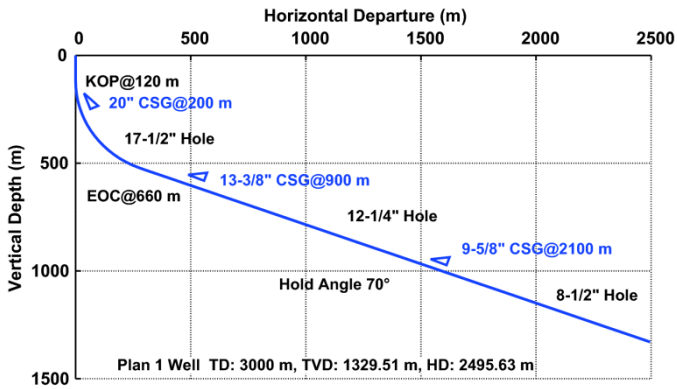
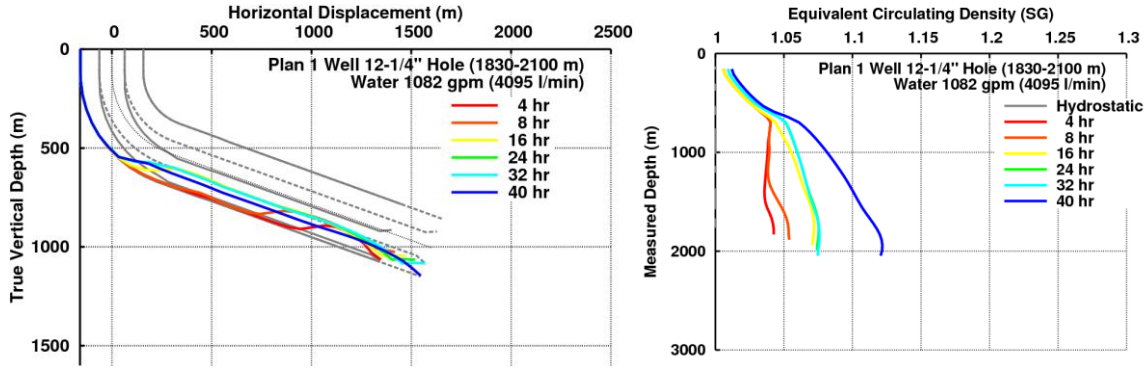


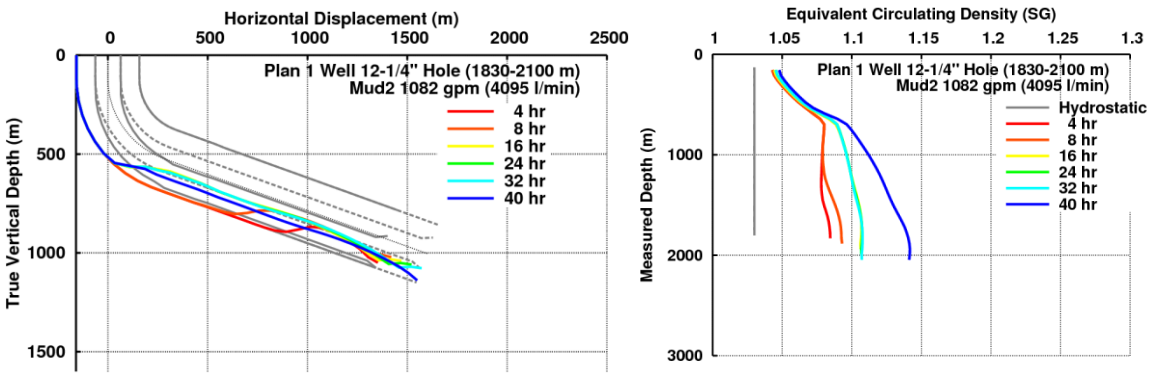
Figure 8: Well trajectory and casing program for Plan 1 model well.

3.2 Simulation Results and Discussion

The simulation results for the 12–1/4-in hole section are shown in Figure 9. Because of the mud pump capacity, a larger hole diameter generally relates to a smaller available maximum annular velocity. Here, we assume that two sets of 800 hp, 8–1/2-in stroke triplex mud pump systems (e.g., NOV 8-P-80 mud pump), typical for a 3,000-m-class land rig, is used. If we use the smallest (6–1/4-in) liners, this mud pump has a maximum circulation rate of 1,082 gpm, and the corresponding annular velocity is approximately 1.08 m/s.



(a) Water



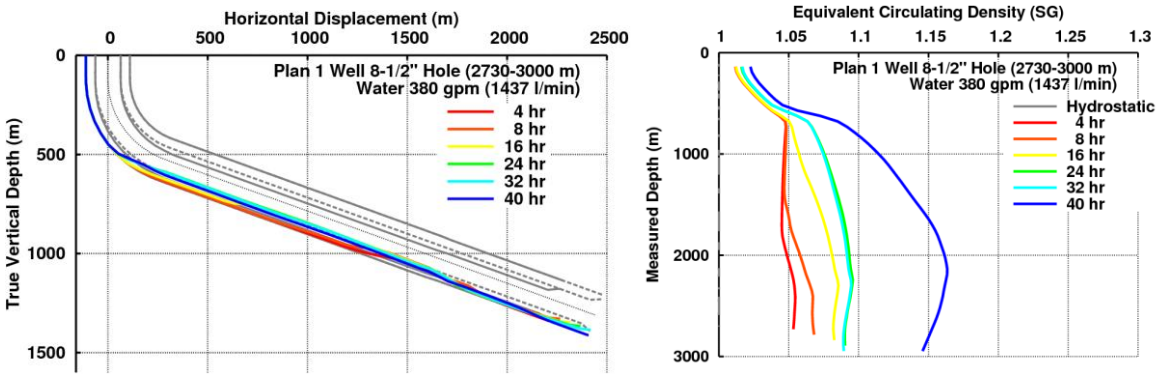
(b) Mud 2 (bentonite mud)

Figure 9: Simulation results for Plan 1 model well 12–1/4-in hole section.

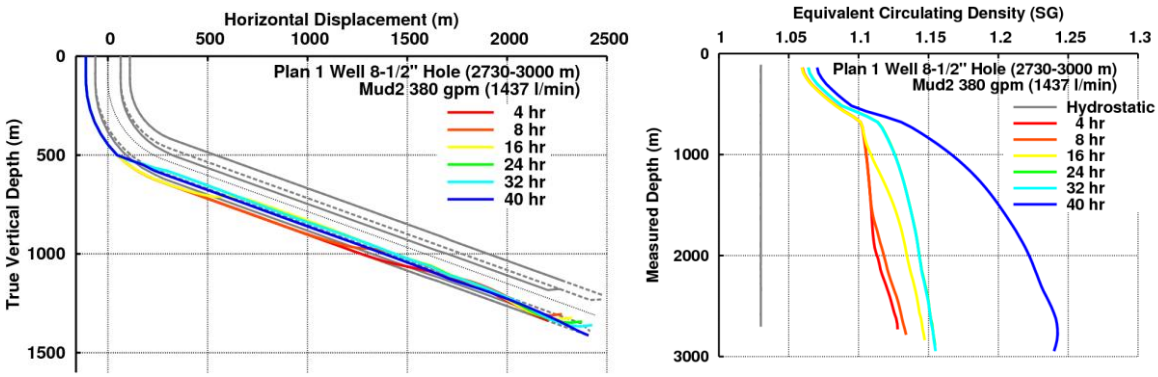
According to the CTFLS experiments demonstrated in the previous study (Naganawa and Okabe, 2013), the desirable annular velocity is approximately 1.4 m/s; therefore, a maximum circulation rate of 1,082 gpm is insufficient for completely avoiding cuttings bed formation. However, relatively good hole cleaning that allows some extent of cuttings deposition can be achieved, and ECD can be maintained at a relatively low rate even with such cuttings deposition for Water and Mud 2 cases.

Simulation results for the 8–1/2-in hole section with a mud flow rate of 380 gpm, which corresponds to 1.0 m/s annular velocity, are shown in Figure 10. The results show that effective hole cleaning can be achieved at this flow rate. However, ECD was greater than that of the 12–1/4-in hole section, particularly in Mud 2 case. To suppress ECD increase and avoid lost circulation and

borehole instability problems, a lower viscosity fluid and slightly higher flow rate are preferable, and a decrease in cuttings bed height is required. However, care should be taken because an excessive flow rate causes an unexpected ECD increase.



(a) Water



(b) Mud 2 (bentonite mud)

Figure 10: Simulation results for Plan 1 model well 8-1/2-in hole section.

The simulated cuttings bed heights in this study are lower than those presented in our previous study (Naganawa and Okabe, 2013) because of the modification of the friction factors in the simulator model. Additional experimental and field data are required for further modification of the model.

4. CONCLUSION AND RECOMMENDATIONS

Determined on the basis of this study, the recommendations for drilling fluids and hydraulics in drilling long, extended-reach geothermal wells are summarized in the following points:

- From the simulation study, a mud flow rate corresponding to 1.0 m/s annular velocity can achieve effective hole cleaning for a long extended-reach geothermal well with a 2,500-m horizontal departure, using low-density, low-viscosity drilling fluids.
- ECD is likely to increase in the drilling of small-diameter long tangential hole sections; drilling with water is a good option for suppressing frictional pressure loss in the annulus.
- Because PWD measurement is not always available, the results of prior hydraulics research must be considered in the planning phase; however, a hydraulics simulator that can predict ECD behavior with high accuracy has not been developed thus far.

ACKNOWLEDGEMENTS

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