Development of the Well Trajectory Prediction System as a Part of the MWD System for Geothermal Wells

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ABSTRACT

MWD (Measurement while drilling) system for geothermal wells has been developed by NEDO (the New Energy and Industrial Technology Development Organization) since 1991. As a part of this system, the drilling support system has been also developed. The well trajectory prediction system is one of this drilling support system including the well trajectory planning system, the well trajectory visualization system, the temperature analysis system and so on, and this system will be used for prediction of well trajectory while drilling and for design of BHA (bottom hole assembly) before drilling. We discussed about the theory of the well trajectory prediction system and its case studies in this paper.

1. INTRODUCTION

Among the costs of geothermal development, the cost of geothermal well drilling occupies a large part. When drilling a geothermal well, the main objective area is complex formation where there are many hard and interrupted formations, and lost circulation layers under high temperatures. Accordingly, equipment is easily damaged and there are several drilling problems such as lost circulation, collapse, and sticking. On the other hand, in many cases, geothermal development areas are subject to environmental preservation regulations and therefore the technique (directional drilling technique), which is able to drill many directional wells from the same area, is increasingly required. In this situation, in order to promote geothermal development, it is necessary to conduct geothermal well drilling effectively, correctly, and inexpensively. Therefore, in fiscal 1991 NEDO began the development of MWD system for geothermal wells which allows the surface personnel to acquire bottom hole data (direction, inclination, temperature, pressure, etc.) in real time and to analyze. Its features include the development of detection equipment which acquires, transfers and calculates bottom hole information under high temperatures while drilling geothermal wells. This MWD system also includes the analysis system which conducts the management of well trajectory and evaluates geothermal wells based on bottom hole data. We are now aiming at real usages for geothermal wells.

Temperature specification of this MWD tool is 200 deg. C while operation and 220 deg. C survival.

Measurement items are azimuth, inclination and tool face, gravity or magnetic, weight on bit, torque on bit, bottom hole temperature, bottom hole pressure, and tool temperature.

Data acquired from the MWD tool are used for directional control and well evaluation using the drilling support system which we will introduce bellow.

2. DRILLING SUPPORT SYSTEM

The drilling support system consists of the directional control support system and the well evaluation support system. The structure of this drilling support system is as Fig. 1. This drilling support system uses both bottom hole data from the MWD tool and surface data from mud logging or other measuring equipment.

The directional control support system is used for real time well trajectory monitoring mainly and also used for planning and prediction of well trajectory while and before drilling.

The well evaluation system is used for simulation of bottom hole temperature and formation temperature while drilling.

In this paper, we will discuss the well trajectory prediction system which is a part of the directional control support system.

3. WELL TRAJECTORY PREDICTION SYSTEM

For well trajectory prediction, we developed program based on equations (Jogi et al., 1988) of equilibrium for BHA to calculate the force acting on bit and the Ho's (1987) definition of bit anisotropy to determine the direction of drilling.

(1) EQUILIBRIUM OF BHA

Equations (Jogi et al., 1988) of equilibrium for

BHA have the following form:

$$EIy^{IV}=Tx'''-Wy''-\omega_0 w_1 z\sin\beta$$
$$EIx^{IV}=-Ty'''-Wx''+w_1\sin\beta$$
$$GJ\omega_0=T=\left[1-2\left(\frac{EI}{GJ}\right)\right]Ta \qquad (1)$$

where, EI; the bending stiffness, GJ; torsional stiffness, Ta; torque on bit (TOB), W; weight on bit (WOB), w_1; effective weight per inch of BHA including buoyancy due to drill mud, β; angle of inclination and, ω_θ; the angle of twist per unit length. The proper boundary conditions for the above equations are:

1) at z=0 : x(0)=y(0)=0, (zero displacement)
x"=(0)=-(T/EI)y'(0)
y"=(0)=(T/EI)x'(0) (2)

2) at z=L : $x(L)=X_L$, $x''(L)=\kappa_x$
$y(L)=Y_L$, $y''(L)=\kappa_y$ (3)

where, (X_L, Y_L) and (κ_x, κ_y) are the local coordinate and curvature of the well bore at z=L (i.e., position of the drill bit).

It can be shown by Liarng (1998) that the proper solution of Eq. (1) is

$$x(z)=A_1\cos m_1 z+A_2\sin m_1 z+A_3\cos m_2 z$$
$$+A_4\sin m_2 z+B_1 z^2+\frac{Ey}{W}z+B_2 \qquad (4)$$

$$y(z)=A_5\cos m_1 z+A_6\sin m_1 z+A_7\cos m_2 z$$
$$+A_8\sin m_2 z-B_3 z^3+B_4 z+\frac{Fy}{W}z+B_6 \qquad (5)$$

where

$$B_1=\frac{(T\omega_\theta+W)w_1\sin\beta}{2W^2}$$
$$B_3=\frac{\omega_\theta w_1\sin\beta}{6W}$$
$$B_4=\frac{[\omega_\theta(T^2+WEI)+WTJw_1\sin\beta]}{W^3} \qquad (6)$$

The remaining constants, m_1 and m_2, $A_1 \ldots A_8$, B_5, and Fx and Fy are to be determined from the characteristics equation of Eq. (1), and from the boundary conditions Eqs. (2) and (3).

(2) DRILL AHEAD MODEL

A drill ahead criterion for calculating the wellpath is developed based upon Ho's definition of bit anisotropy I_b. Assume that a new BHA is placed into an existing wellbore, and that a constant WOB is applied and the BHA drills ahead. In order to calculate the drilling direction, it is necessary to consider the bit tilt angle θ_{bt} and the bit inclination angle θ_{bi}. In describing the force on bit, the superscript (b) denotes the force on the bit surface, and the subscripts "L" and "a" denote the lateral and axial component of the force vector (i.e., the force parallel to and perpendicular to the bit face), respectively (ref. Fig. 2). For convenience, the force components shown in the figure are forces acting on the rock. The magnitude of force on bit, the bit inclination and tilt angles $(\theta_{bt}, \theta_{bi})$ can be calculated from the static BHA analysis.

If the bit has an equal cutting ability in both the axial and lateral directions (i.e., Ib=1), the action of side cutting would reduce the lateral force $F_L^{(b)}$ to zero and the drill direction would be along the direction of force vector $F^{(b)}$. On the other hand, if the bit has a limited side cutting ability (i.e., Ib<l), the direction of drilling would be along the direction of the resultant vector of forces $I_b F_L^{(b)}$ and $F_a^{(b)}$. Based on the definition of bit anisotropy, the corresponding bit inclination angle $\theta_I^{(b)}$ can be written as:

$$\tan\theta_I^{(b)}=I_b\frac{F_L^{(b)}}{F_a^{(b)}} \qquad (7)$$

The inclination angle of the drillpath (or the direction of drilling) is therefore

$$\gamma=\theta_{bt}+\tan^{-1}\left(I_b\frac{F_L^{(b)}}{F_a^{(b)}}\right) \qquad (8)$$

Therefore, when a new BHA is introduced into the existing hole, one expects an abrupt change in direction of drilling resulting in a kink (or dog-leg) at the onset. From this point onward, the lateral force exerted on the rock is expected to vary smoothly and the direction of wellpath is expected, after a short transition length, to coincide with the predicted drilling direction.

(3) ROTARY DRILLING

Above mentioned theory is for static BHA, that is drilling using DHM. When rotary drilling is used, if rotating speed of BHA reaches the resonant RPM of drill collar, lateral motion of drill collar would become unstable and whipping of drill collar would occur. Once drill collar becomes unstable and whipping, direction of force on bit is also unstable. Therefore it is difficult to control directional drilling. To avoid this, we developed program to find resonant RPM based on Yew's (1994) equation as below.

$$\omega res=\frac{1}{2m}\left[\sqrt{-\mu^2+4m(EIn_1^4+Tn_1^3-Wn_1^2)}\right] \qquad (9)$$

where

$$n_1 = \frac{\pi}{L} - \frac{T}{4EI}$$

ω_{res} : Resonant RPM
EI : Bending stiffness
m : Unit weight of drill collar
μ : Mud viscosity
T : Torque on Bit
W : Weight on Bit
L : Length of drill collar

4. CASE STUDIES

(1) MUD MOTOR DRILLING

For this study, we used mud motor BHA as bellow.

Tools	OD	ID	Length
Bit :	12-1/4"		0.5m
Mud motor :	8"	2.25"	7.5m
NMDC :	8"	2.25"	9.0m
DC :	8"	2.25"	135.0m

We assume this BHA is in straight hole of 10 deg. inclination.

a) BENT SUB ANGLE

Bent sub is the most important tool to determine angle change when mud motor is used.

Fig. 3 shows the force on bit when tool face is set 0 deg. or up word. According to bent angle increase, building force is increasing lineally. Fig. 4 shows inclination change as depth change. In this case, build rates of 2.2, 2.8, 3.5, 4.0 and 4.7 deg./30m are predicted using 1.00, 1.25, 1.50, 1.75 and 2.00 deg. bent sub angle respectively.

b) TOOL FACE

Tool face is only controllable parameter for changing azimuth direction. Effect of tool face is studied. Fig. 5 shows build force on bit according to tool face angle change. In this figure, positive force is for build and negative is for drop inclination. If tool face is set 90 deg., build force is a little negative. As a result of this, inclination will drop slightly.

Fig. 6 shows the difference of inclination by difference tool face angle as depth change.

c) WEIGHT ON BIT

Weight on bit (WOB) is important drilling parameter for build rate control when rotary BHA is used. However, effect of weight on bit for mud motor BHA is not known well. Therefore we study for mud motor BHA. Fig. 7 shows the build force when tool face is set 0 deg. Build force increases large when WOB is small but saturate above 10 ton WOB. Fig. 8 shows inclination change as depth change. Effect of WOB change is a little.

d) COMPARISON WITH FIELD RESULT

Fig. 9 shows a comparison of the prediction result and the field result at kick off stage are in good agreement.

(2) ROTARY DRILLING

a) RESONANT RPM

Fig. 10 shows the relation between WOB and resonant RPM with difference of drill collar length. In this analysis, we use 12-1/4" for bit diameter, 8" OD and 2.25" ID for drill collar and 1.2 SG and 10 CP for mud property. The threshold of resonant RPM becomes lower as length of drill collar and weight on bit increase.

Normal numbers of drilling RPM and WOB are hatched on Fig. 10. For instance, if drill collar length between stabilizer is 15m, resonant RPM is much higher than normal rotary RPM. However if this length is more than 18m, it might be almost resonant RPM.

Using the resonant RPM simulation results, drillers could take care of the rotary RPM to avoid reaching resonant RPM.

b) ROTARY BHA

When rotary BHA is used, BHA configuration is the most important for directional drilling. Effect of BHA configuration is studied.

Fig. 11 shows the inclination change using different BHA configurations, which are build, hold and drop BHA. 12-1/4" bit, 8" OD and 2.25" ID drill collar are used in this study. Configurations are as Fig. 11 and initial inclination is 30 deg. and bore hole is straight. 6 deg./30m build rate and 1.3 deg./30m drop rate are predicted by build BHA and drop BHA respectively in this study.

c) STEERABLE MOTOR

Steerable motor is not common to use for geothermal drilling in Japan yet but will be in near future. Special consideration are needed to predict well trajectory when steerable motor is used, because there is bent housing and this bent housing is rotated.

When steerable motor is used for rotary drilling, it is possible to predict well trajectory using equivalent bit and lower stabilizer size as Fig. 12 and putting zero for bit anisotropy index, Ib. Fig. 13 shows that trajectories using steerable motor system with rotation and without rotation.

(3) FUTURE FUNCTION

Now, this system predicts the well trajectory based on the known BHA and drilling condition such as weight on bit, well shape and so on. However, unknown formation effect has been ignored. Therefore we are now improving the system to include the formation evaluation scheme.

5. CONCLUSION

The new MWD system, which is one of the NEDO geothermal R&D projects, includes the analysis system, so called the drilling support system which conducts the management of well trajectory and evaluates geothermal wells based upon bottom hole data. In this paper, we particularly explained the well trajectory prediction theory and showed the results of case study which are the effect of bent sub angle, tool face and weight on bit, then compared with field result when mud motor is used. We also showed the results of case study of resonant RPM, effect of BHA configuration and steerable motor when rotary drilling is used.

Through case studies and comparison, we are confident of real usage with the new MWD system, therefore we decided to implement an inversion scheme in this system.

ACKNOWLEDGMENTS

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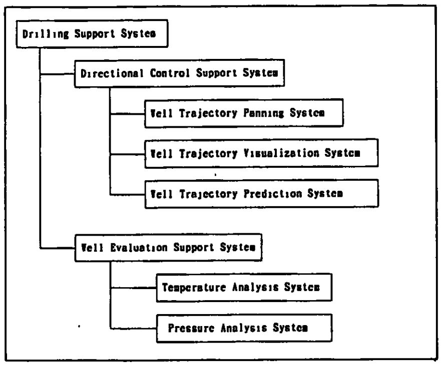

Fig. 1 Structure of the drilling support system

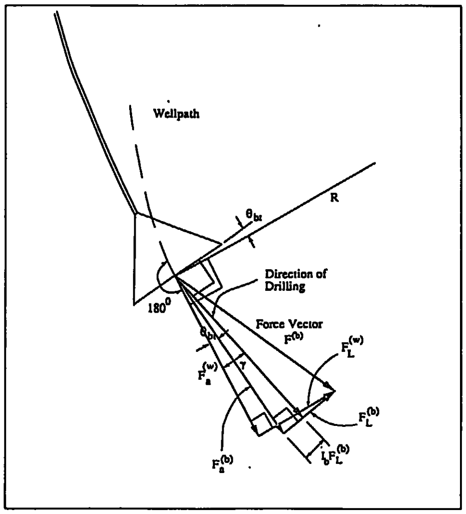

Fig. 2 Drill ahead model

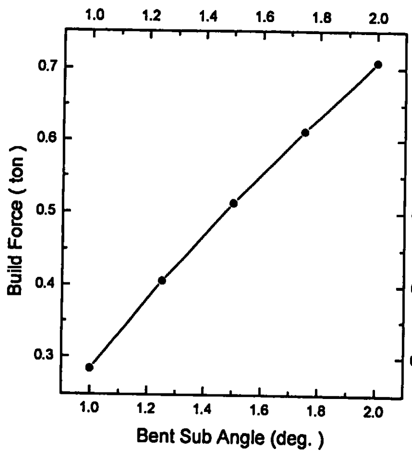

Fig. 3 Effect of bent sub angle (build force) (According to bent angle increase, building force increasing lineally.)

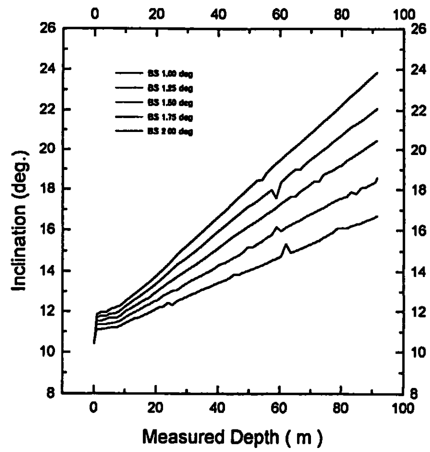

Fig. 4 Effect of bent sub angle (inclination) (Inclinations are predicted for each bent sub angle.)

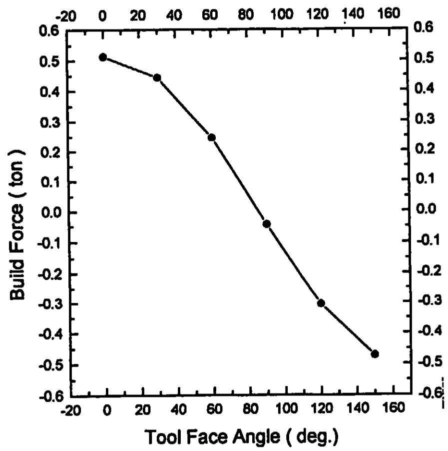

Fig. 5 Effect of tool face angle (build force) (Positive build force is for build and negative is for drop inclination.)

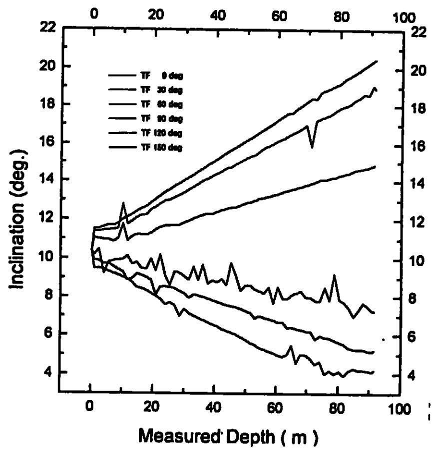

Fig. 6 Effect of tool face angle (inclination) (Inclinations are predicted for different tool face angle.)

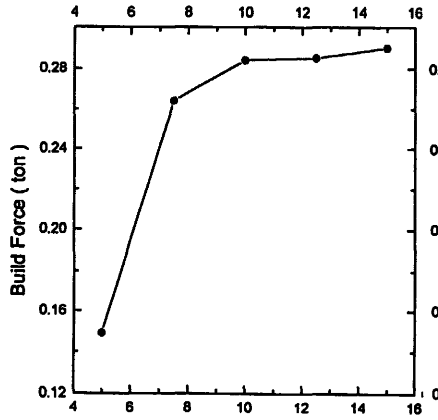

Fig. 7 Effect of weight on bit (build force)
(Build force increases large when WOB is small but saturate above 10 ton WOB.)

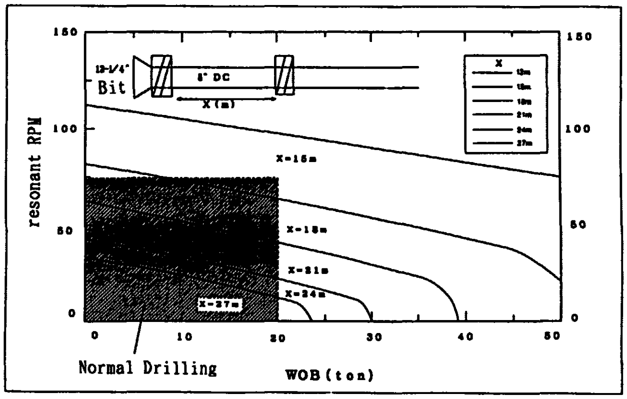

Fig. 10 Resonant RPM

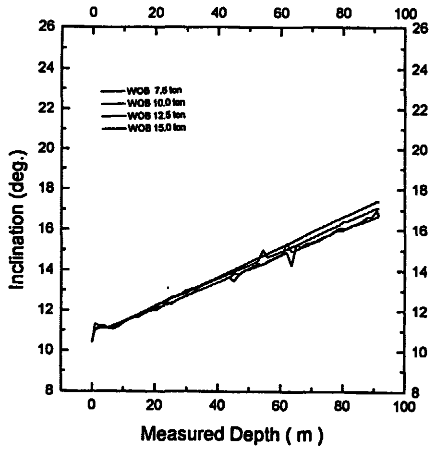

Fig. 8 Effect of weight on bit (inclination)
(Effect of WOB change are a little.)

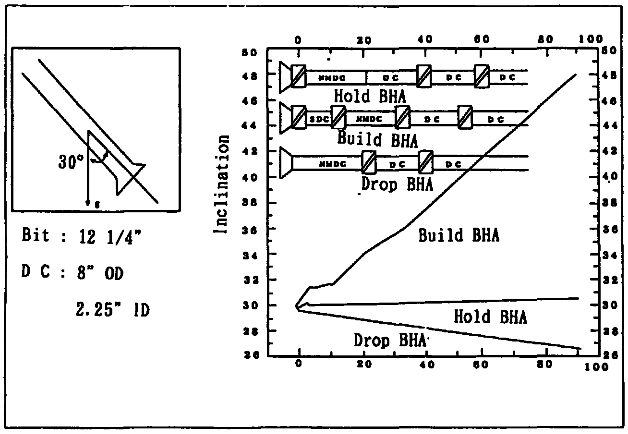

Fig. 11 Effect of BHA configuration
(Inclinations are predicted for each BHA configuration.)

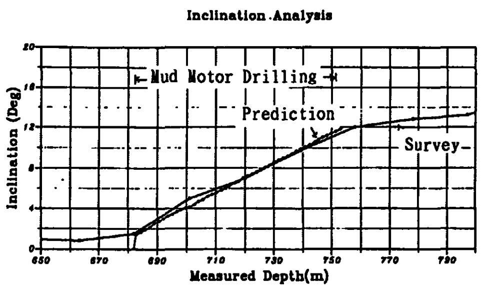

Fig. 9 Comparison with field result
(Predicted well trajectory and field survey result are in good agreement.)

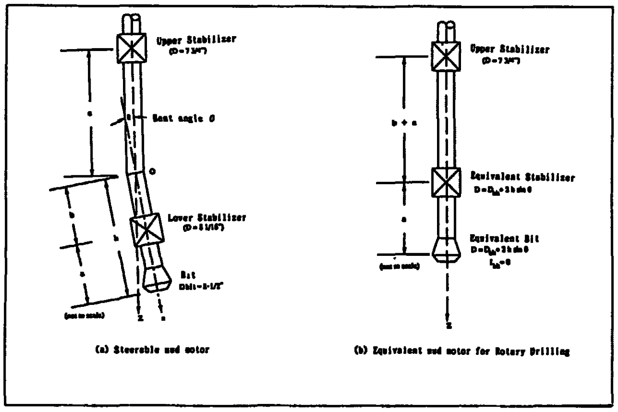

Fig. 12 Equivalent steerable mud motor for rotary drilling

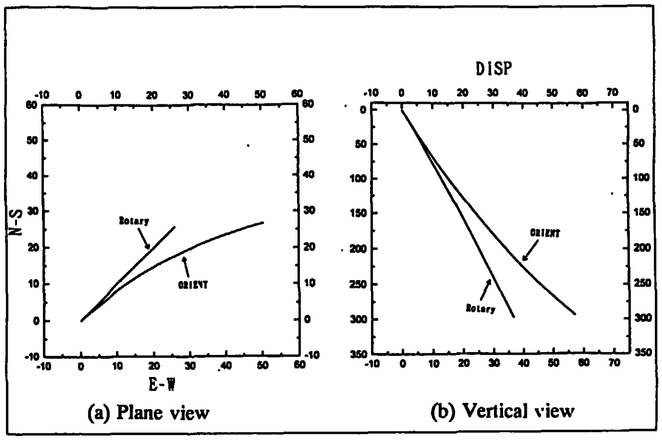

Fig. 13 Well trajectory by stecrable mud motor