Modelling and simulation of deflection mechanism in rock drilling processing

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Abstract. With the development of social economy, hydraulic drilling machine has been widely used in the tunnel bridge, water conservancy projects and mining. In the process of construction, the drill rod of the hydraulic rock borer in drilling perforating process will produce deviation. It is often caused by the drilling efficiency and reduces the drilling hole scrap, seriously hindered the development of construction technology of drilling and blasting. Through the hydraulic drilling machine drill rod in the drilling cutting process of force analysis, drill rod in horizontal and vertical direction of the mechanical model are established. The relationship between the drill rod force and deflection of drilling in the drilling process is derived. At the same time, build ADAMS mechanical model, and the drilling process is simulated to find the relationship between the depth of drilling and the offset and offset angle. On this basis, the mechanical mechanism of borehole deviation of hydraulic rock drill is clarified, which provides a theoretical basis for the hydraulic rock drill hole deviations.

1. Introduction
Since the drilling borehole blasting technology is the main means of tunnelling and mining, so hydraulic rock drill equipment has been widely developed and applied [1,2]. But the hydraulic rock drill impact drilling process, the drill rod by force and torque will cause drilling deviation. It can lead to the failure of hole, causing great harm to the drilling process [3,4]. The study of the mechanical model of drilled borehole skew is generally only the vertical drilling conditions, and the mechanical model of other working conditions is not studied. The working conditions of the piston, the drill rod and the rock during the drilling process are analyzed. Through the force analysis model of the hydraulic rock drill in the horizontal and vertical conditions of drill rod, which construct the simulation model. Using software ADMAS respectively moving-parts mechanical load analysis, which obtain the mechanical characteristics of borehole deviation.

2. Dynamical model of drill holes
In the process of rock drilling, the rod of hydraulic drilling machine movement and drilling holes position is consistent.so the amount of deflection of the drill rod is the amount of deflection of the blast hole. To build the right one of drill rod mechanical model is very important in research and analysis skewed drilling holes.
2.1. Horizontal rock drilling conditions
When the hydraulic rock borer rod drill in the horizontal direction, we can ignore the weight of the drill rod and moving parts weight; horizontal drilling when the drill rod force model showed in Fig1, converted into the force diagram shown in Fig2.

![Fig.1 Horizontal drilling rod stress model](image1)

![Fig.2 Horizontal drilling rod force diagram](image2)

In the figure, \( F_T \) is the rocker propulsion force, \( M \) is the rotational moment, \( \alpha \) is the inclination of rock surface, \( F_S, F_Z, N \), respectively, for the rock face of the drill edge of the decline in resistance, rotation resistance and support force; \( M_1 \) is the rock facing the bit rotation torque moment (the \( F_Z \) produce the torque when moved to the center of mind), \( M_2 \) is the drilling system bending moment (\( N, F_S \) produce the bending moment when moved to the center of mind); set the drill bit radius is \( R \), drill rod length is \( L_Z \).

Horizontal rock drilling conditions ignore the impact of gravity on the drill rod, and from Fig2, in the yoz plane of the drill rod is subjected to the force in the z-axis direction; in the yoz plane drill rod bending moment is \( M_2 \).

According to the material mechanics deflection and bending moment formula, the drill rod in the yoz surface displacement and rotation angle is:

\[
\Delta z = \frac{(F_s \cos \alpha - N \sin \alpha)L_z^3}{3EI} + \frac{M_2 L_z^2}{2EI}
\]  

(1)

\[
\theta_{yoz} = \frac{(F_s \cos \alpha - N \sin \alpha)L_z^3}{2EI} + \frac{M_2 L_z}{EI}
\]

(2)

\( EI \) is the bending factor in the formula. From fig 2:

\[
M_2 = (F_s \sin \alpha + N \cos \alpha)R
\]  

(3)

\[
\sum F = 0; F_T - N \cos \alpha - F_s \sin \alpha = 0
\]

(4)

\[
F_S = f \cdot N
\]

(5)

In the formula: \( f \) is the friction coefficient. (3), (4), (5) were substituted into (1), (2) simplified:
\[ \Delta z = \left( \frac{L_z^2(f \cos \alpha - \sin \alpha)}{3EI(f \sin \alpha + \cos \alpha)} + \frac{RL_z^2}{2EI} \right) \times F_t \]  
(6)

\[ \theta_{yoz} = \left( \frac{L_z^2(f \cos \alpha - \sin \alpha)}{2EI(f \sin \alpha + \cos \alpha)} + \frac{RL_z^2}{2EI} \right) \times F_t \]  
(7)

Due to shaft pressure:

\[ F_d = F_t \]  
(8)

So:

\[ \Delta z = \left( \frac{L_z^2(f \cos \alpha - \sin \alpha)}{3EI(f \sin \alpha + \cos \alpha)} + \frac{RL_z^2}{2EI} \right) \times F_d \]  
(9)

\[ \theta_{yoz} = \left( \frac{L_z^2(f \cos \alpha - \sin \alpha)}{2EI(f \sin \alpha + \cos \alpha)} + \frac{RL_z^2}{2EI} \right) \times F_d \]  
(10)

Drill rod rotation resistance:

\[ F_z = \frac{M_1}{R} \]  
(11)

Regardless of the nature of the rock, the relationship between the rotational resistance moment \( M_1 \) and the drill shaft pressure can be expressed by the following formula:

\[ M_1 = kF_d^i \]  
(12)

In the formula, \( K \) is the proportional coefficient between the rotational resistance and the shaft pressure; \( i \) is the exponential greater than zero.

By the material mechanics deflection and corner formula, we know that makes the drill bit in the xoy plane displacement and rotation angle is:

\[ \Delta x = \frac{KF_d^iL_z^3}{3REI} \]  
(13)

\[ \theta_{yoz} = \frac{KF_d^iL_z^2}{2REI} \]  
(14)

2.2. **Vertical drilling conditions**

Drill rod vertical drilling force model shown in Fig 3, to be converted into drill rod vertical drilling when the force diagram shown in Fig4:

![Fig.3 Vertical drilling force model of drill rod](image1)

![Fig.4 Drill rod vertical drilling force diagram](image2)
In the Fig. 3, $W_1$ is the weight of the components (mobile drill body weight); $nW_2$ is the weight of the drill pipe. As can be seen from Fig. 4, the drill bit is subjected to the $y$-axis force in the $yoz$ plane: $F_y = F_x \cos \alpha - N \sin \alpha$; The bending moment in the $yoz$ plane is $M_z$.

Axial pressure:

$$F_d = nW_2 + W_1 + F_T$$

According to the level of the drill rod horizontal force calculation method can also be derived from the drill down the rock, the offset and angle in the $yoz$ plane are:

$$\Delta y = \left[ \frac{L_y^2 (f \cos \alpha - \sin \alpha)}{3EI} + \frac{RL_y^2}{2EI} \right] \times F_d$$

$$\theta_{yoz} = \left[ \frac{L_y^2 (f \cos \alpha - \sin \alpha)}{2EI} + \frac{RL_y^2}{EI} \right] \times F_d$$

$F_z$ causes the displacement and rotation of the drill bit in the $xoy$ plane:

$$\Delta x = \frac{kF_{d1} L_y^2}{3REI}$$

$$\theta_{xoy} = \frac{kF_{d1} L_y^2}{2REI}$$

3. The establishment of simulation mathematical model

Hydraulic rock drill in the drilling process mainly by the piston, drill rod, rock composition of the rock movement system, the parameters of the model are as follows:

3.1. Piston

In the hydraulic rock impact mechanism, the piston in the role of hydraulic oil reciprocating impact drill rod to transfer energy to break the rock, so as to achieve the purpose of drilling [5,6]. The ideal piston motion is shown in Fig. 5, where $T$ is the piston motion period, $T_1$ is the piston stroke time, $T_{21}$ is the return acceleration time, $T_{22}$ is the return braking time, $T_2$ is the piston return time, $V_{m0}$ is the maximum return speed, $V_{max}$ is the maximum speed.

Professor Xiangbi Yang of Central South University of Technology introduced the design of abstract variables into the design of rock drill [7], proposed: abstract variables. According to the design of the hydraulic rock drill machine selected $=0.3$, $V_{max}=8$ m/s, $T=1/35$ s.

![Fig.5 Ideal motion law curve of the piston](image)

According to the above data, the corresponding results are calculated as the maximum speed $V_{m0}=3.42587$ m/s, the return acceleration time $T_{21}=0.016326$ s, the return acceleration $a_1=-210$ m/s$^2$, $...
stroke acceleration \( a_2 = 933.33 \text{ m/s}^2 \). Thus, the trajectory equation of the piston can be derived as follows:

\[
S = \begin{cases}
-\frac{1}{2} \cdot 210t^2; (t \leq 0.016326) \\
-0.02798 - 3.42857t + \frac{1}{2} \cdot 933.33 \cdot (t - 0.016326); (0.016326 < t \leq 0.02857) \\
8t; (0.02857 < t \leq 0.03107)
\end{cases}
\]  

(20)

According to the study of the rock borer, the distance between the piston and the drill rod is 20 mm, the piston to 8 m/s speed movement with the drill rod collision.

3.2. The force on the drill rod

In the process of drilling, the drill rod is mainly driven by the propulsion force and the rotational force, in which the propelling force makes the drill rod fully in contact with the rock to ensure the efficiency of the-rocking; the rotational force mainly cuts the rock to fully peel the rock.

3.2.1. Drive power. The drive power of the rock borer is not only related to its own performance and parameters. It is also related to the physical behaviour of rocks that are broken by rocks [8]. According to engineering practice, Professor Xiangfu Yang of Central South University put forward the optimal solution of the empirical formula of drive power:

\[
F_r = \left( r - \frac{8}{100} \right) \cdot \left( \frac{f_1}{\beta} \right) \sqrt{2mE + GSIN\beta + GCOS\beta \cdot \mu}
\]  

(21)

In the formula \( r \)-dimensionless universal coefficient; gravity of \( G \)-rock drill; \( m \)-impact piston mass; \( E \)-single impact energy; \( \beta \)-inclination of rock drill; \( f_1 \)-the impact frequency; \( \mu \)-coefficient of friction between the rock drill and rail.

3.2.2. Turning power. So that the study of the value-free hydraulic rock borer for the object, the rotational speed is 250 r/min and the torque is 150 N.m.

3.3. Collision contacts

In the formula: \( F_c \) is the contact force; \( K \) is the stiffness of the collision object; \( \Delta x \) is the crush deformation of the two collision objects; \( x \) is the independent variable, \( e \) is the index; \( d \) is the infiltration parameter; \( C \) is the damping coefficient.

\[
F_c = K \times (\Delta x)^e - step(x, 0, 0, d, C) \times x
\]  

(22)

Piston and drill rod collision parameters, and drill rod and rock collision parameters, as showed in Table 1 and Table 2[9].

| Sign | Name | Number |
|------|------|--------|
| K    | Stiffness factor [N/mm] | 100000 N/mm |
| C    | Damping coefficient | 50 |
| c    | Force index | 1.5 |
| d    | Permeation parameter[mm] | 0.1 mm |
| Vs   | Static friction transition speed [mm/s] | 0.1 mm/s |
| Vd   | Dynamic friction transition speed[mm/s] | 10 mm/s |
| Mus  | Coefficient of static friction | 0.08 |
| Mud  | Coefficient of Dynamic friction | 0.05 |
3.4. Rock
The rock is modelled as an elastic model. It is divided into shock loading and unloading two stages. The function expression is as follows:

$$F = \begin{cases} K_1 u \\ F_{max} - \delta K_1 (u_{max} - u) \end{cases}$$

(23)

In the formula: There are expressions of loading and unloading. The rock load stiffness sign is $K_1$, generally between 0.5 and 2. $u$ represents displacement; unloading stiffness is $\delta K_1$. $\delta$ is the unloading factor $1 \leq \delta \leq \alpha$; $F_{max}$, $u_{max}$ is the maximum working force of the rock deformation process and the corresponding displacement; the working medium mechanics model shown in Figure 6.

Granite was studied as $K_1 \approx 4300$ N/mm; unvalued range of 0.2 ~ 0.4, the rock performance parameters into the above expression.

3.5. Model establishments
In the PORE software according to the design of the piston rod, etc. model is created, and then all the parts are assembled in the assembly. Save the model diagram in x-t format.
3.6. Parameter Setting
After the model is imported into ADMAS/View, the material and quality of each structure are set up [10]. The constraint between the piston and the drill rod is set as a cylindrical pair. The rock is set as a fixed constraint, and the drill rod is added with a dotted line. The piston motion trajectory is added to the piston according to the step function. The gyroscopic moment and the drive power function are respectively loaded on the drill rod [11]. Put the rock mathematical model and parameters into the software to set up. After the completion of all the parameters set, horizontal drilling and vertical drilling model in ADMAS is obtained.

4. Simulation results and analysis
4.1. Effect of the amount of skew of the horizontal drilling
In the set rock drilling depth of 0.5 m, in ADAMS simulation model and simulation data collection, then use the resulting MATLAB data fitting. The relationship between the depth of chisel and the angle of YOZ and XOY plane offset during horizontal drilling as showed in Figure 7 and Figure 8. In the process of horizontal drilling, the drilling depth of YOZ and XOY plane offset relationship curve, as showed in Figure 9 and Figure 10.

![Horizontal drilling simulation test of offset in the X direction](image1)

Fig.7 Horizontal drilling simulation test of offset in the X direction

![Horizontal drilling simulation test of offset in the Z direction](image2)

Fig.8 Horizontal drilling simulation test of offset in the Z direction
Figure 7 and Figure 8 can be seen in the horizontal drilling process with the depth of the chisel, the amount of deviation of the rock drilling also increases. When the drilling depth is 0.5 m, the maximum peak of the skew in the X direction is 0.015 m, and the offset in the Z direction reaches 0.012 m.

In terms of angle, it can be seen from Fig. 9 and Fig. 10 that the maximum offset angle is 5 degrees on the YOZ surface and 4.95 degrees on the XOY plane. The offset angle is negative due to the selection of the drilling direction, and the offset angle gradually increases with the depth of the drilling.

4.2. The effect of the amount of skew in the vertical chisel
As with the horizontal rocking simulation, the change in the depth of the chisel and the Y and X-direction offset during the down-drilling process was obtained at a depth of 0.5 m, as shown in Fig. 11 and Fig12. the relationship between the depth of the chisel and the XOY and YOZ plane offset angles is shown in Fig. 13 and Fig.14.
Fig. 12 Downward drilling simulation test offset in the X direction

Fig. 13 Downward drilling simulation test of offset angle in XOY surface

Fig. 14 Downward drilling simulation test of offset angle in YOZ surface

In the downward drilling process, it can be seen from Fig. 11 and Fig. 12 that the offset in the Y direction is 0.006 m when the penetration depth is 0.5 m, but the offset in the X direction is 0.02 m. Due to the rock borer and the gravity of the drill rod in the downward direction of the action, resulting in the X direction of the offset is much greater than the Y offset.
In terms of the angle, from Fig. 13 and Fig. 14 can be seen, when the drilling depth of 0.5 m, the XOY plane has an offset angle of 4.3 degrees, due to the negative cause of the direction; the offset angle of the YOZ plane is 3.5 degrees.

4.3. Comparison of two working conditions
From the general trend of the simulation curve, the horizontal and downward deflection and offset angles in the rocking process are proportional to the depth of the drill. In the offset, the horizontal direction ignores the weight of the rock drill and the drill rod. The downward chucking offset in the X direction reached 0.02 m significantly greater than the horizontal drill in the X-direction offset of 0.015 m. In the other two directions: the difference between the level of the tangled Z-direction and the downward-shot Y-offset is due to the difference in axial thrust and coefficient.

In terms of angle, horizontal drilling in the XOY plane and YOZ plane of the offset angle of 5 degrees and 4.9 degrees; and the downward chisel offset angle of 4.3 degrees and 3.5 degrees. This is because when the simulation software in the horizontal direction of the drill rod weight or have a certain effect on the angle.

5. Conclusion
(1) By constructing a mechanical model of a rock drill rod, mathematical expressions obtained offset and offset angle of the horizontal and vertical drill rod drilling conditions to obtain the main parameters of axial thrust and deflect deflection relationship.

(2) The main components of the drilling process are analyzed and the physical model was established by PROE. Using ADMAS simulation analysis, in the process of horizontal cutting and down drilling, the relationship between the depth of penetration and the offset and offset angle is obtained, and get the relationship curve. It is found that the depth of penetration has a great influence on the amount of skew and skew angle.

(3) Through the modeling and simulation analysis of the skew mechanism of drilling, it provides important reference for studying the corresponding drilling skew mechanics model and drilling correction method.

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References
[1] B. Lundberg, P. Collet. (2010) Optimal wave with respect to efficiency in percussive drilling with integral drill steel [J]. International Journal of Impact Engineering, 37: 901-906.
[2] Servet Demirdag, Nazmi Sengun, et al. (2014) Variation of vertical and horizontal drilling rates depending on some rock properties in the marble quarries [J]. International journal of mining science and technology, (02):269-273.
[3] WU Wanrong, WEI Jianhua, ZHANG Yongshun, et al. (2001) Mechanism of large diameter deep hole drilling holes deviation and its control program [J]. Transactions of Nonferrous Metals Society of China, (01): 153-156.
[4] HE Xiaoping, WANG Yi, YAN Jie, et al. (2013) Causes and countermeasures of drilling deflection in the construction of the submersible drilling rig [J]. Road Machinery & Construction Mechanization, (01): 73-75.
[5] ZHANG Kai. (2015) The research and optimization design of valve controlled hydraulic drilling machine [D]. Jiangsu: China University of mining and technology, 3:13-17.
[6] LIU Zhong, ZOU Yu, ZHANG Kai, et al. (2015) Research on the working state parameters of gas - liquid combined impact hammer [J]. China Mechanical Engineering, (24): 3370-3374.
[7] YANG Xiangbi. (1993) Hydraulic rock drill evaluation index abstract design variables [J]. Rock drilling machinery & pneumatic Tool, (02): 2-7.
[8] YUE Wenhui, LIU Deshun, WU Xianming, et al. (2007) Environmental friendly hydraulic shock modeling and numerical simulation of rock dynamics [J]. Engineering Sciences, (08): 57-61.

[9] DONG Fuxiang, HONG Jiazhen. (2009) Research on multi-body system dynamics collision problem [J]. Advances in mechanics, (03): 352-358.

[10] CHEN Liping, ZHANG Yunqing. (2005) Dynamic analysis of mechanical system and ADMAS application tutorial [M]. Beijing: Tsinghua University Press, 4: 43-53.

[11] LI Zhiguo, LI Xibing, WANG Bin. (2011) Hydraulic rock drill impact dynamic simulation system based on Sim-Hydraulics [J]. Journal of Central South University (Natural science edition), (12): 3835-3843.