Reamer design variables for curved path drilling

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Abstract. The paper presents the algorithm for assessment of design variables for a warm reamer in curved path drilling. The value of soil deformation by the reamer casing versus its length in the curved path drilling is determined in mathematical modeling. The formula of the maximum length of the reamer casing versus the casing diameter and the guide parameters is obtained.

1. Introduction
Drilling is one of the basic procedures in mineral exploration as well as in open cast or underground mining. Hole making is often a key operation in many special underground construction services such as laying of utility lines, installation of arch bolts, soil reinforcement, etc. [1].

Lately in hole making, it is increasingly more frequently required to change the hole path in order to get to the wanted point in the underground space either from a mine or from the ground surface. It is necessary to design a hole rerouting control system. To this effect, it is required to engineer a deflector gear for drilling tool, to determine its design values and capabilities subject to physical and mechanical properties of rocks, as well as shape and size of drilling tool.

The analysis of approaches to the drilling tool rerouting during hole making in soil at the Institute of Mining, SB RAS [2] shows that the best functional designs of deflectors use the engineering solutions based on the re-configuration of the drilling and on the change of the impact point.

The simple methods to deflect drilling tool use deflectors in the form of an asymmetric wedge. When such wedge rotates, the deflecting force incessantly changes its action direction, and deflection is absent as a result. It is necessary to stop rotation and to apply axial force to the wedge. Deflection will be oriented in opposite direction to the skew plane of the wedge.

Such tools have found application mainly in directional horizontal drilling in soil or in loose rocks [3]. At the stage of re-routing, with rotation being stopped, a hole is made by puncture, i.e. radial displacement of rocks. The maximum diameter of holes is 300–350 mm in many puncture tools. This constraint is governed by a significant increase in the energy intensity of the process in case of larger diameter hole making. When it is necessary to drill boreholes more than 200 mm in diameter, the process is implemented by steps, with a larger diameter reamer at each step. Alongside with the higher energy intensity in larger diameter hole making by the method of puncture with radial displacement and compaction of soil, the zone of deformation in adjacent soil enlarges. The zone of notable deformation in soil makes 4–5 diameters of the hole. The zone of perceptible deformation is two times larger [4]. This phenomenon can cause risk of damage of closely spaced utility lines or swelling up of ground surface above the hole.
2. Numerical modeling and results
Reaming of a rathole not only reduces the hole construction time and removes the hole diameter constraint but also relaxes surrounding compact soil from high stress. Figure 1 shows the borehole reamer with a guide. The reaming facility is composed of casing $1$, worm $2$ and drill bit $3$ with mobile mechanism connection $4$ to the guide $5$.

![Figure 1. Reamer with guide: (a) basic diagram; (b) design diagram.](image)

The drill tool–rock interaction during the change of the drilling path is the subject of many research works using various procedures [5–8]. Using these research findings, it is possible to determine the design values of the reamer for curved routing of ratholes.

Using the study [8] as a basis, we consider the design diagram of the reamer for rathole drilling along the curved path (Figure 1b). When the axial force $F_x$ is applied to the reamer with the guide deflected by an angle $\alpha$, the reamer front gravitates in the direction of the curved hole (upward in Figure 1), which causes a certain deflection force $F_t$ on the casing pipe, which results in deformation $h_a$ and $h_b$ of soil being compacted. Under the axial force $F_x$, the guide tends to keep its position relative to the reamer, which induces the force $F_p$ that cases deformations $h_c$ and $h_d$ in soil. Depending on the axial force and the deflection angle of the guide, the values of $F_t$ and $F_p$ are found from the formulas:

$$
F_t = F_x \tan(\alpha),
$$
$$
F_p = F_x \sin(\alpha).
$$

Thus, the design criterion for the reamer is the condition that at the front of the reamer, $h_b$ is higher or equal to the deformation $h_c$ at the back end of the tool. With this condition fulfilled, it is possible to deform soil by the reamer with preserving the required curved path of drilling.

Aiming to determine design values of the reamer, we find their interaction with the value of soil settlement. When a soil layer is compacted under distributed load, settlement occurs due to compaction. According to [9], the formula of settlement is given by:

$$
S = h a_0 p,
$$

where $h$ is the height of the soil layer under compaction, m; $a_0$ is the soil compressibility ratio; $p$ is the pressure applied to soil, Pa.

The ratio of soil compressibility is calculated using the deformation modulus $E_0$:

$$
a_0 = \frac{\beta}{E_0},
$$

where $\beta$ is...
where $\beta$ is the conversion factor to transit from the constrained modulus $E_0$ to the total deformation modulus $E$ (sand—0.76, sandy loam—0.72, clay loam—0.57, clay—0.43).

The height of the soil layer under compaction is found from the assumption that the pressure applied on soil by the tool is sufficient for soil deformation. The sufficient pressure criterion is the structural strength of soil, i.e. the excess of this value causes deformation in soil.

![Figure 2. Distribution pattern of vertical pressure in soil under press-tool under the action of concentrated force.](image)

The vertical pressure distribution in soil under a press-tool subjected to the action of concentrated force (Figure 2) is found from the equation [9]:

$$p(z) = \frac{3F}{2\pi z^2}.$$

At the depth $z = h$ the pressure lowers to the value of structural strength of soil. Accordingly, at the depth more than $z = h$ deformation effect on soil is absent. The thickness of the soil layer under compaction is:

$$h = \sqrt{\frac{3F}{2\pi p_{\text{struct}}}}.$$

The structural strength is governed by the type of soil and its porosity, and can be found using the studies described in [10].

The pressure generated in soil is found from the condition of equilibrium in the system in Figure 3, with the force $F_t$ applied on the reamer and the force $F_p$ applied on the guide:

$$\begin{align*}
\sum F_z &= 0, \\
\sum M_o &= 0.
\end{align*}$$

![Figure 3. Force application on (a) reamer) and (b) guide.](image)

We solve (6) with regard to a value [11]:
\[ n = \frac{L_x}{lx}, \]  

which is introduced to describe an averaged position \( lx \) of the turn point on the body as against its length \( L_x \), and obtain the formula for evaluating pressures:

\[
\begin{align*}
pa &= \frac{Ft(n - 1)}{2RLt}, \\
pb &= \frac{Ft(3n - 1)}{2RLt(n - 1)}, \\
pe &= \frac{Fp(n - 1)}{2rLp}, \\
pd &= \frac{Fp(3n - 1)}{2rLp(n - 1)}.
\end{align*}
\]  

By differentiating the domain of pressures and after finding resultant forces in every short segment, we use formulas (5) and (2) and calculate the depth of the soil layer being compacted and the value of pressing-in (settling) of the body in the hole walls, \( ha, he, hc \) and \( hd \), per drilling interval of 1 mm in length.

In compliance with this procedure, a mathematical model is constructed and is used to determine the values of pressing-in of the reamer and guide. Soil under compression was sand lay having density \( \rho = 1750 \text{ kg/m}^3 \); the diameter and deflection angle of the guide were \( d = 130 \text{ mm} \) and \( \alpha = 1^\circ \), respectively. Lines 1, 2 and 3 in Figure 5 demonstrate the value of the guide settling \( hc \) versus its length for the guide 1, 1.5 and 2 m long, respectively. These lines are the boundary conditions for the required length of the reamer.

![Figure 4. Settling \( hb \)–length curves for reamer.](image)

Curves 4, 5 and 6 in Figure 4 show the dependence of the settling and body length for the reamer for casing diameters 250, 300 and 350 mm, respectively. The analysis of these results allows drawing a conclusion that the length of the first deflectable unit of the casing is governed by the length of the guide and by the diameter ratio of these elements. The length of the first deflectable element of the casing should be shorter for shorter guide and larger-diameter reamer. The maximum length can be found from the empirical formula:

\[ Lt = \frac{r}{R} Lp - 0.02 \left( \frac{Lp - 0.5}{0.5} \right). \]  

3. Conclusions

The presented algorithm allows a preliminary estimate of design variables and capabilities of the deflecting reamer. Maneuvering ability of the reamer can be improved by optimizing its design.
variables. For example, it is possible to increase the maximum length of the reamer by using the reamer bit of the larger diameter relative to the casing diameter, which expands the maneuvering space for the reamer.

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