Determining deviation parameters when sinking horizontal wells in soil

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Abstract. A schematic diagram of a device for deflecting a hole trajectory during horizontally directed auger drilling is proposed. The problem of deflector interaction with soil under static loading is considered. Using modified Cam Clay model for clay soils of the Ansys finite element package, the parametric problem on determining the dependence of well axis deflection angle and the value of well deviation per running meter of its length on the bevel angle of the front plane of rock cutting tool is solved. The optimal value of the angle is calculated.

1. Introduction
The technologies of trenchless pipe laying, which are currently widely used in construction engineering, have proven their effectiveness and efficiency. However, they are not without flaws and need to be improved. The most commonly used technology involves drilling a pilot well along a specified trajectory and then expanding it to the required diameter by pulling reamers. Trajectory monitoring is carried out using a geolocation device, and a control is carried out by turning drill head, which has a bevel on the front surface. At the same time, it is obvious that the diameter of the pilot well is limited, and there is a limit for its expansion due to soil compaction.

This problem is partly solved in the technology of horizontal directional drilling (HDD) by removing soil from the well using drilling mud. However, a side effect of this is the violation of the geometry of the wells, and sometimes the collapse of the soil mass and the breakthrough of the drilling fluid to the daylight surface [1]. Casing auger drilling technology avoids problems of such kind. Nevertheless, most often, it requires preliminary laying of a pioneer well [2]. This is largely due to the need to control the trajectory of the well to ensure its exit into a specified area of the underground space.

Due to above, it seems promising to analyze the possibility of developing such design diagrams of trajectory correction devices that are applicable not only in puncture technology, but also in auger drilling without laying a pilot well [3]. Figure 1 schematically shows the design of the front part of the auger, which cutting tool is made in the form of a split disk, tilted on the auger axis. During rotation, such a tool forms a cone-shaped working face. When moving forward without rotation, the soil reaction creates a force on the tilted surface, consisting of axial and radial components. The radial component is the deflection force. The magnitude of the stroke without rotation is limited due to the formation of a soil plug. If the deviation obtained is not enough, then after one or several rotations of the auger without axial feed, the correction can be performed again required number of times.
2. Method of research

To evaluate the possibility of achieving needed effect, it is necessary to define the dependence of a deviation of the working body on front surface bevel angle to the longitudinal axis. The problems of determining soil deformation under arbitrary boundary conditions, taking into account plastic strain, do not have an analytical solution. They can be solved using numerical methods, the most widespread of which in geomechanics is the finite element method (FEM) [4]. The method has been developing since the 1950th and now due to development of computer technologies makes it possible to solve nonlinear problems with complex boundary conditions. In turn, the development of numerical methods has given an impetus for a broader study of the properties of soils and the creation of various strength models based on them. Also various software systems were designed for computing geomechanical problems, such as Ansys, Solidworks, PLAXIS, PHASE2, etc.

Figure 1. Design concept of deflection device: 1 – tool, 2 – auger, 3 – tube casing.

Figure 2. Design scheme of well deviation during auger drilling: 1- tube casing, 2- joint, 3-deflection device.
The well deviation design scheme is shown in figure 2. The structure consists of the tubular casing 1, revolute joint 2, and deflection device 3. The deflection device 3 is a part of the casing, the front of which is closed with a cutting tool located at an angle $\alpha$ to the screw axis. The body of the deflection device is jointed to the main tube 1. To the back face of which pressure $P$ is applied. The beveled face of the deflection device and its outer cylindrical surfaces as well as the surface of the tube 1 are in contact with the soil. Due to the reaction forces of the soil, the device deflects. It is necessary to find out how efficiently the well will be deviated. It should be assumed that the angle of deflection of the head will be influenced by the value of the angle $\alpha$, pressure $P$, soil properties, and tube diameter. To check this assumption, it is necessary to solve the contact problem of the interaction of the structure with the soil.

The test problem is solved using the Ansys complex, which has a library of materials and the ability to select a soil deformation model. For geological materials there are several models used in Ansys: Mohr - Coulomb, Drucker - Prager, Cam - Clay, Menetrey - Willam, Porous Elasticity, Jointed Rock.

The so-called Cap Models have been developed at the turn of the 1960-es [1–7] to describe the behavior of normally compacted clays and later were expanded for overconsolidated dispersed soils, as well as half-rock and rock. They at first include the Cam-Clay model and the modified Cam-Clay model. Cam – Clay models are elastoplastic with isotropic hardening. For the first time a model with a logarithmic yield surface was developed by K. Roscoe, A. Schofield and C. Wroth [7, 8]. Then, in [9, 10], a model was proposed with an elliptical yield surface, called the modified Cam-Clay. The yield surface is plotted in $p$-$q$ coordinates, where

$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3),$$

$$q = \frac{1}{2}(\sigma_1 - \sigma_3),$$

and $\sigma_1, \sigma_2, \sigma_3$ – principal effective stresses.

The graphic interpretation of the model is shown in figure 3a. The line $q = M_0$ is the critical state line (CSL) for a given soil and characterizes the relationship between the stress deviations and the value of $p$. The coefficient $M$ depends on the angle of internal friction $\varphi$ as follows [4]:

$$M = \frac{6 \sin \varphi}{(3 - \sin \varphi)}$$

It is believed that the $M$ values for clays lie in the range from 0.7 to 1.2 [9], which corresponds to value $\varphi$ from $18^\circ 40'$ to $30^\circ$.

The model is based on the following assumptions:

- Under normal compression by pressure $p_0$ in the OAp0 zone, only small recoverable elastic deformations are possible. Outside the zone, plastic strain appears, and their level is the same on the entire surface of Ap0.
- The yield surface is also the surface of plastic potential, the vector of plastic strain is normal to the yield surface (the associated flow rule).
- The work of plastic deformations is determined only by shear stresses $q$, i.e. $dA = pMd\gamma^p$ (in the Cam-Clay model), and in the modified model it is defined as $dA = p\sqrt{(d\nu^p)^2 + (Md\gamma^p)^2}$, where $\nu^p, \gamma^p$ - plastic strain vector components.

The yield surface equation then describes an ellipse:

$$p^2 - pp_0 + \frac{q^2}{M^2} = 0.$$
Figure 3. a – graphic interpretation of modified Cam-Clay model, b – typical behavior for clays under normal compression (oedometer) test [4].

The accumulation of plastic strains with stress increasing expands the elastic region and the associated elastic surface shifts to the position $A'p_0'$. In this case, the volumetric plastic strain is constant regardless of the loading path and is equal to the strain of the soil during isotropic compression from pressure $p_0$ to pressure $p_0'$. Porosity factors under loading and swelling (unloading), respectively, are:

$$e_\lambda = e_{\lambda 0} - \lambda \ln p,$$
$$e_k = e_{k 0} - k \ln p.$$

In order to determine $\lambda$ and $k$ coefficients, it is necessary to perform normal compression test or oedometer test and plot the dependence of $e$ on $\ln(p)$. For weakly cohesive soils, it will be a straight line (figure 3b). Thus, it is necessary to determine only three experimental parameters $M$, $\lambda$ and $k$.

Based on the design model, a finite element 3D model symmetric about the XOY plane to reduce computing costs was built. The soil is imitated by a 1x1x2m rectangular parallelepiped. The diameter of the tube and the head is 0.219 m, the length of the tube is 1 m, the length of the head is $l = 0.5$ m. For the head-joint-pipe system, displacements perpendicular to the XOY plane are fixed, and the tube end is fixed in the vertical direction. A pressure of $10^8$ Pa is applied to the end of the tube. The problem is solved parametrically with a change of the angle $\alpha$ from 25° to 60° stepping by 5°, and the horizontal displacement $X_A$ of A point was also recorded. The deflection angle is determined as

$$\beta = \sin^{-1} \left( \frac{Y_B - Y_A}{l} \right) \frac{180}{\pi},$$

where $Y_A$, $Y_B$ are vertical displacements of points A and B.

The ratio of deflection to translational displacement $\beta/X_A$ is also determined. The calculation is carried out for three different cases of mesh refinement, with a cell size of 0.3, 0.1 and 0.05 m.

3. Results
An example of the calculation option is shown in figure 4. All calculation results are summarized in the Table 1.

Figure 4. Vertical displacement (m) in plane of symmetry of the model at $\alpha=25^\circ$. 

| Value | Description |
|-------|-------------|
| 0.028280 | 0.019282 |
| 0.001284 | 0.010283 |
| 0.007714 | 0.016713 |
| 0.025712 | 0.034710 |
| 0.043709 | 0.044309 |
Table 1. The values of the deflection angle, horizontal displacement and linear deviation depending on the bevel angle at different cell size.

| Cell size, m | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
|-------------|----|----|----|----|----|----|----|----|
| α, deg      | β, deg | X_A, m | β/X_A, deg/m |
| 0,3         | 3,92 | 4,03 | 2,97 | 3,19 | 2,32 | 2,70 | 2,20 | 1,70 |
| 0,1         | 3,14 | 3,25 | 3,08 | 3,08 | 2,68 | 2,58 | 1,86 | 1,4 |
| 0,05        | 2,43 | 2,73 | 2,51 | 2,41 | 2,16 | 1,96 | 1,79 | 1,44 |

According to the results of calculations, it can be concluded that the bevel angle (α) increases, the deviation angle (β) decreases, changing from 4 to 1.5° (figure 5a). Moreover, with mesh refining, the dependences become smoother and shallower, which indicates the mesh convergence. So, for a mesh with cell size of 0.05 m, the dependency of the deflection angle (β) has a nearly linear form and is in a narrower range of 2.77 – 1.44°. The curve of the ratio of deflection to translational displacement (β/X_A) also looks smoother with decreasing cell size (figure 5b). According to the results of the calculation with an element size of 0.05 m, it can be concluded that the most preferable values of the bevel angle (α) of the head will be located near the 40° mark, what may be due to close values of components of the soil reaction in longitudinal and vertical directions. With an increasing of bevel angle (α), the longitudinal component of displacement decreases (see Table 1), since the force of longitudinal resistance increases.

Figure 5. a – dependence of the head deflection angle β on the bevel angle α for different cell size, b – dependence of the ratio of deflection to longitudinal displacement on the bevel angle α for different cell size.

4. Conclusions
The proposed schematic diagram of the device for deviating the trajectory of a well during horizontal directional auger drilling can be applied to design a mechanism for controlling the trajectory of a well directly in the process of auger horizontal drilling. To obtain a more complete information of the proposed system characteristics, further studies are required based on the results obtained, in particular, the calculation of the interaction with the soil of a rock-cutting tool in the form of a disk.
located at an angle to the axis of rotation and having one or more radial cuts for soil evacuation. Also the dependence of well deviation on geometric parameters of a tool should be found.

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