

BOREHOLE TRAJECTORY CONTROL: TECHNOLOGIES AND METHODS FOR ACCURATE ORIENTATION IN EXPLORATION DRILLING

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ABSTRACT. The growth of mineral resources exploration and the fast pace of development of directional drilling technology, along with borehole surveying difficulties, are challenges to the correct execution of the borehole path and the target reach. The subject of analysis in the current paper are the methods used in technical resources of exploration borehole positioning, the following trajectory control and successful reach of the desired target diameter of the engineering task. In particular, the following are discussed: the setup according to a given geodetic datum, and the precise borehole surveying according to a correct reference point, technique and technology. Six methods of curve description are listed. The method chosen for the calculations is the minimum curvature method for intensity and linear extrapolation, and the results are presented in a tabular form.

Key words: directional, deviation, geodesy, extrapolation.

КОНТРОЛ НА ТРАЕКТОРИЯТА НА СОНДАЖИ: ТЕХНОЛОГИИ И МЕТОДИ ЗА ПРАВИЛНО ОРИЕНТИРАНЕ В ПРОУЧВАТЕЛНОТО СОНДИРАНЕ

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РЕЗЮМЕ. Ускореното проучване за минерални ресурси и бързото развитие на технологията за проучвателно наклонено-насочено сондиране, заедно с трудностите при измерването на пространственото положение на сондажите, се явяват предизвикателства за правилното определяне на траекторията на сондажа и попадането в неговата целева зона. В настоящия доклад са анализирани методите, използвани в техническите средства за позициониране на проучвателния сондаж, последващото проследяване на траекторията и успешното достигане до инженерната цел в планираната целева зона. В частност се разглеждат: точното задаване по конкретен геодезистки модел и прецизното измерване на сондажа според правилната референтна точка, техника и технология. Изброени са 6 метода на описване на криви, като конкретно е избран да се използва методът на минималната крива за описание на интензитет и линейна екстраполация, а резултатите са изобразени таблично.

Ключовидуми: насочено, отклонение, геодезия, екстраполация.

Introduction

Building on a previous study, where a survey interval of 30-50 is sufficient for borehole trajectory monitoring, a proper setup of a borehole and optimal deviation control afterwards, during the actual drilling, is a crucial part of any borehole execution. In many cases, the exact path of the boreholes is not accurately known, making it uncertain whether they follow the intended trajectory.

This is a complex of knowledge about setting up the drilling rig, borehole surveying, and planning. This study continues a previous work of the authors' on borehole survey interval optimisation, extending to an analysis on surveying technique and trajectory evaluation. In this paper, the basics of borehole setup and deviation control will be covered, along with several examples of what impact it makes if technological resources are not used correctly.

The actual shape of the Earth is best approximated by a geoid, which represents an equipotential surface of the Earth's gravity field. For practical calculations, this surface is simplified using a reference ellipsoid, most commonly defined within the World Geodetic System 1984 (WGS84) (Hofmann-Wellenhof et al., 2001). Given its irregularity, it is too complex to make calculations on it; therefore, a theoretical model is used, called Ellipsoid, to match the actual surface of the Earth in order to make calculations. Therefore, a geodetic datum is used in order to bring the Ellipsoid to the reality as one of the common ones used is the World Geodetic System 84 (WGS 84). Knowing the starting point of reference is crucial for proper borehole planning.

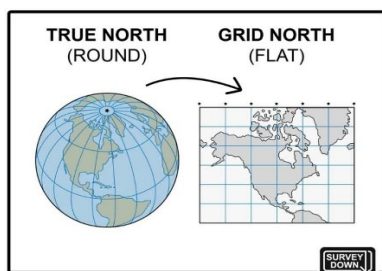


Fig. 1. True North/Grid North

(Source: <https://www.surveymdown.com/which-ways-north>)

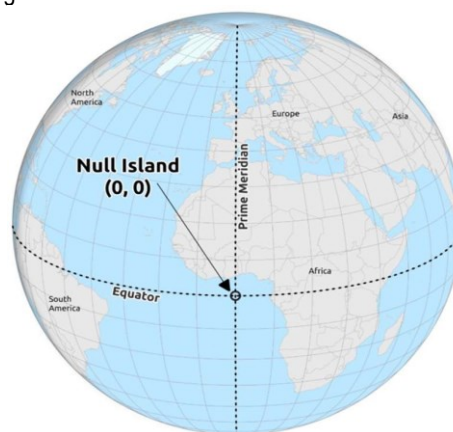


Fig. 2. The Null

(Source: <https://mapscaping.com/>)

Coordinate systems used in borehole positioning can be classified as geocentric, geographic, and projected systems, each serving a specific role in spatial referencing and mapping (Torge, 2001):

- Geocentric – they use the X, Y, Z from the centre of the Ellipsoid (i.e. The Null, Fig.3);
- Geographical – they use Latitude, Longitude, and Height; Projection – they using Easting Northing and Elevation in meters. (Jamieson, 2012).

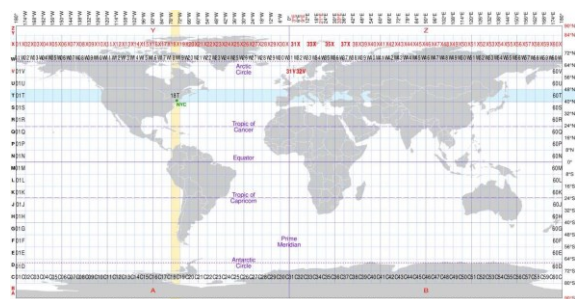


Fig. 3. Universal Transverse Mercator coordinate system

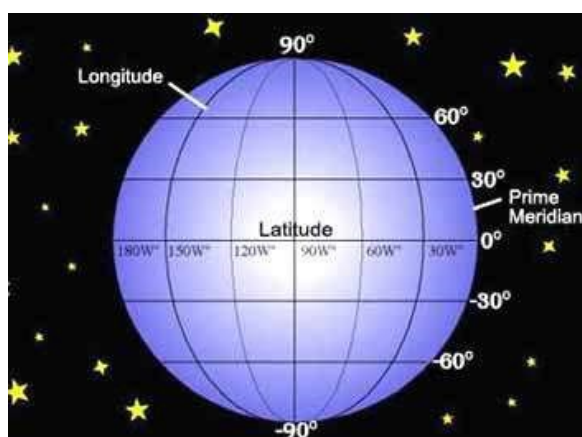


Fig. 4. Grid Coordinate system

Since a reference map is used, several other definitions will be given:

Defining the types of north and their differences is of fundamental importance. As the Earth has a geographic field and magnetic field, both fields have North. True North is the geographic field's north, and Magnetic North is that of the magnetic field. The difference between True North and Magnetic North varies over time due to changes in the Earth's magnetic field, requiring continuous correction using magnetic declination models (NOAA, 2023). Grid North, on the other hand, is the one on the map we are using. It varies between 0 and 3 degrees, depending of the location of the borehole position (Fig. 5). Hence, this paper will examine how that affects the borehole trajectory.

As the geoid has an irregular form and the map is the Earth stretched in a rectangle, there is a difference between the models. Therefore, the technological resource used in order to set up a survey needs a borehole to be set up into the correct north as it differs related to the location of the hole. Failing to apply that, the trajectory tolerance may result in an unsuccessful engineering task.

The Azimuth gives us the horizontal direction compared to the north. The interpretation of geophysical data is strongly dependent on measurement accuracy and proper spatial

referencing, as variations in subsurface properties may lead to misinterpretation of structural conditions (Tomova et al., 2025).

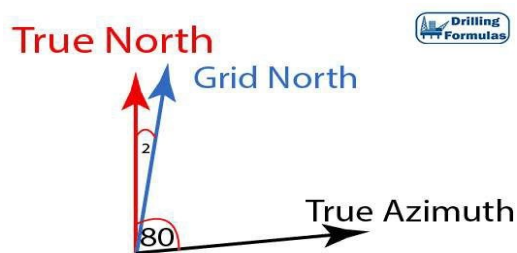


Fig. 5. The three types of North
(Source: drillingformulas.com)

Quality control in borehole surveying

After the correct set up of the borehole, the key part of the successful borehole completion is the correct borehole surveying. Geographic and magnetic methods are used to determine the spatial position and curvature of the borehole at depth, forming the basis for trajectory control and geological interpretation (Dimovski, 2007).

There are two main types of survey tools used depending on the surrounding factors, which have a similar working principle.

1. Gyroscopic tools (Fig. 6) – they use the geographic field as a reference and are subdivided into: North seekers and reference tools, where Azimuth is set up manually. North seekers find their reference themselves, whereas the other type should be manually set according to the data available about the Azimuth value.



Fig. 6. Gyroscopic survey tool

2. Magnetic survey tools, similarly, use the Geomagnetic field as a reference; therefore, the magnetic declination must be added/subtracted. It is set to measure the total magnetic vector in nanoteslas (nT), an amount sensitive enough to note a disturbance in the measurements.

Both methods of surveying (the geographic and the magnetic methods) will give incorrect data if wrong datum is used. Also, the method and interval of the borehole surveying gives a different borehole model regarding the survey interval or method of single-, multishot, and continuous plus survey overlap when multiple. Gyroscopic survey tools reduce the overlap of station, which results in more precise borehole trajectory. The closer the north – which is their reference point – the more the likeliness of incorrect data is.

Linear exploration examples

Six main methods are used to describe the trajectory of a borehole:

- Tangential
- Balanced Tangential
- Minimum Curvature

- Average Angle Method
- Spline Method
- Radius of Curve.

In the linear extrapolation example, the Minimum Curvature Method is used. As Grid North can vary $\pm 3^\circ$, the study is set with a 1° step to up to 3° as error factor in the extrapolations. The example of a vertical hole and an inclined hole is to express the function of the effect of the setting and surveying of a borehole with negligible difference in the Azimuth value.

Borehole 1 in Table 1 is 750 meters in depth with setup inclination of -51.1° and Azimuth of South-East 153° . Thus, the further from the vertical, the bigger impact small deviations of the Azimuth will have compared to the situation when they are closer to the vertical holes.

Special cases of experienced significant natural deviation higher than DLS 1-2 will not be discussed. The survey interval is normally set between 30-50 meters. The focus here is more on the correct setup of the drill rig; in order to drill along the correct trajectory and hit within the target diameter. The first step of setting the borehole correctly is crucial for the other steps following, e.g. borehole surveying. Accurate borehole trajectory control contributes both to achieving geological objectives and maintaining safe drilling operation, particularly in areas containing existing or abandoned mine workings. The redevelopment of previously operated mining projects further increases the need of reliable mapping of underground infrastructure and accurate borehole positioning during deposit evaluation and subsequent drilling activities

Borehole 1 has a specification: 750 meters design depth, -51.1° inclination, and 153° azimuth. Target diameter would not be used, as only differences of the trajectory and the target will be calculated through linear extrapolation.

Table 1. Extrapolation data from hole 1

Depth (m)	3D distance with linear extrapolation (m)		
	1°	2°	3°
200	2.2	4.4	6.6
350	3.8	7.6	11.5
500	5.4	10.9	16.4
750	7.5	15.2	23.2

Borehole 2 has specifications: 1172 m design depth, -87.43° dip, and 141° . The aim is to investigate the significance of inclination regarding the sensitivity of the Azimuth which affects the trajectory.

Table 2. Extrapolation data from hole 2

Depth (m)	3D distance with linear extrapolation (m)		
	1°	2°	3°
200	0.11	0.26	0.41
400	0.30	0.62	0.93
600	0.35	0.78	1.24
1172	2.95	3.18	3.77

The distance between two points is calculated 3-dimensionally (<https://unacademy.com/content/nda/study-material/mathematics/analytical-geometry-three-dimensions-distance-between-two-points/>).

Both boreholes are examined with 3 different scenarios according to the probability of a faulty orientation and incorrect surveying. In **borehole 1**, the inclination is set to be -51.1° from the horizontal plane of the Earth. The purpose is to express the function of the sensitivity of the Azimuth accuracy related to the Inclination of the boreholes. Using the linear extrapolation from each Measured Depth, an arithmetic progression of the deviation of the planned trajectory is obtained and target diameter with an estimated step the difference in distance of Azimuth deviation of 1° . As normally the target diameter is 10% of the total depth, typically 10-20 meters, this proves that improper setting of the borehole might make it impossible to reach it. Therefore, unknowingly ending up with unreached targets results in possible higher cost per value of the drilling program, hitting mining chambers, or in case of infrastructure geotechnical projects, messing up with pipes, cables, or unwanted areas of crucial significance.

In borehole 2, the lesser significance of the Azimuth accuracy according to the projected borehole path is expressed. The difference calculated with a step of a 1° difference of the Azimuth with three examples expresses an arithmetic progression with an average step of the difference in distance with 1 degree Azimuth. Given the deeper target location, it ends up with a difference of 3.77 m compared to 23.2 m at a depth of 750 m for borehole 1.

Conclusion

The results indicate that survey interval cannot compensate for orientation errors. Deriving from the calculated data from both boreholes, it can be concluded that the correct setup followed by surveying is of high significance in order to execute a borehole program correctly and free of risky events. As for the advancement of technology of all types of drilling, knowledge of multiple disciplines is required in order to advance collaterally.

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