Mine Surveying Control of Wells

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Abstract. The article considers the problems of increasing the accuracy and reliability of processing of inclinometric and telemetric data. It provides the review of domestic and foreign references for the topic. It is noted that by no means all the tasks are solved methodically and most effectively. The work proposes the method of processing the inclinometric survey data, which takes into account the data correlation of adjacent intervals. It also provides statistic solution of the task of determining the ellipsoid crossing, undetermined location of well bottom and design tolerance area. The algorithms proposed in the work are realized in program complex “Mining and geodetic networks and survey”. The analysis of error accumulation in determination of well bottom undetermined ellipsoid showed that calculation without taking into account the correlation of adjacent intervals underrated the final error, i.e. the size of undetermined ellipsoid by 20 – 40%. The determination of tolerance area sizes must be performed for a particular deposit or a group of deposits with similar mountainous and geological conditions. The increase in wellbore accuracy requires the increase of instrumental accuracy of telemetric and inclinometric devices.

1. Introduction

The resources of the Earth are quickly running short. The developed oil deposits will be enough for 30–50 years. Large deposits have been under exploitation for a long time and nearly all newly introduced into exploitation deposits refer to difficult ones. The wells are getting longer with longer horizontal areas, that is why effective oil extraction requires high accuracy well boring. In this connection the role of mining and geophysical services is getting more important as they deal with surveying and processing of inclinometric data. The accuracy of telemetric systems which accompany the boring process is still low and does not let perform the well boring with sufficient accuracy. The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) [1] works out, maintains and publishes the standards for industry, contributing to mutual understanding of problems, connected with the research for accurate determination of wellbore hole position [2].

The other large organization dealing with these problems is the Society of Petroleum Engineers (SPE)[3], which together with ISCWSA publishes materials and research [4].

In publications of last years a lot of works are devoted to reliability of well bore position determination [5,6], to the investigation of magnetic inclinometer surveying accuracy [7,8]. Big part of research is taken by gyroscopic orientation accuracy [9,10].
The Russian Federation still uses methodological guidelines for processing inclinometric data [11], which do not comply to modern methods and techniques for well boring. Modern educational materials [12] repeat well-known theories and do not reply to many questions of inclinometric and telemetric data processing. Therefore, a lot of companies develop their own normative documents, for example [13], based on the documents of ISCWSA and SPE.

The authors think that the methods for inclinometric data processing and error accumulation do not take into account the correlations of adjacent intervals in inclinometric measurements, which can underrates the size of the ellipsoid of uncertainty.

The second not fully formalized task is the operation for checking whether an ellipsoid of uncertainty enters the tolerance when checking whether the bottom of the well reaches the point with the design coordinates.

2. Error accumulation of inclinometric survey
When drawing regularities the authors based on the following suggestions:

In the end of each $j$ interval three values are measured:

- $l_j$ – the length of the interval, $m$;
- $\theta_j$ – zenith angle, degrees;
- $\alpha_j$ – azimuth (magnetic), degrees, which constitute the vector $\mathbf{r}_j$ of measurement (fig. 1):

$$
\mathbf{r}_j = \begin{bmatrix}
l_j \\
\theta_j \\
\alpha_j
\end{bmatrix}
$$

The errors of interval values measurement forms the vector

$$
\delta\mathbf{r}_j = \begin{bmatrix}
\delta l_j \\
\delta \theta_j \\
\delta \alpha_j
\end{bmatrix}
$$

It is suggested that the constituents of the vector $\delta\mathbf{r}_j$ are independent random values without systematic displacement and with known standards of $\sigma$ errors, determined by technical characteristics of the used inclinometer. Covariance matrix $K_j$ of the vector $\delta\mathbf{r}_j$ has the view:

The matrix (3) is constant for all intervals in processing of inclinometric measurements.
The measurement errors in intervals are pair-wise independent.

The increment of the axis coordinates for each interval is calculated sequentially and the coordinates of the well axis points are found by summing them. In general view vector $X_k$ of the coordinates of the end of $k$ - interval can be presented by the following expression:

$$X_k = f_1(r_1) + \sum_{j=2}^{k} f_j(r_{j-1}, r_j)$$

(4)

where

$$X_k = \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix}$$

(5)

$a f_j(r_{j-1}, r_j)$ - vector function of coordinate increment on the interval $j$

$$f_j(r_{j-1}, r_j) = \begin{bmatrix} \varphi_x(r_{j-1}, r_j) \\ \varphi_y(r_{j-1}, r_j) \\ \varphi_z(r_{j-1}, r_j) \end{bmatrix}$$

(6)

Functions $\varphi_x(r_{j-1}, r_j), \varphi_y(r_{j-1}, r_j), \varphi_z(r_{j-1}, r_j)$ - scalars.

Vector $\Delta X_k$ of the point $k$ coordinate errors according to the formula (4) is determined by the following expression

$$\Delta X_k = \frac{\partial f_1(r_1)}{\partial r_1} \delta r_1 + \frac{\partial f_2(r_1,r_2)}{\partial r_2} \delta r_2 + \frac{\partial f_3(r_2,r_3)}{\partial r_2} \delta r_2 + \frac{\partial f_4(r_2,r_3)}{\partial r_3} \delta r_3 + \cdots + \frac{\partial f_k(r_{k-1},r_k)}{\partial r_{k-1}} \delta r_{k-1}$$

(7)

Vector partial derivatives are matrices, which with the formula (6) can be written in the following view:

$$\frac{\partial f_j(r_{j-1},r_j)}{\partial r_j} = \begin{bmatrix} \frac{\partial \varphi_x}{\partial \delta r_j} & \frac{\partial \varphi_y}{\partial \delta r_j} & \frac{\partial \varphi_z}{\partial \delta r_j} \\ \frac{\partial \varphi_x}{\partial \delta r_j} & \frac{\partial \varphi_y}{\partial \delta r_j} & \frac{\partial \varphi_z}{\partial \delta r_j} \\ \frac{\partial \varphi_x}{\partial \delta r_j} & \frac{\partial \varphi_y}{\partial \delta r_j} & \frac{\partial \varphi_z}{\partial \delta r_j} \end{bmatrix} = F_{j,j}$$

(8)

And for vector $r_{j-1}$

$$\frac{\partial f_j(r_{j-1},r_j)}{\partial r_{j-1}} = \begin{bmatrix} \frac{\partial \varphi_x}{\partial \delta r_{j-1}} & \frac{\partial \varphi_y}{\partial \delta r_{j-1}} & \frac{\partial \varphi_z}{\partial \delta r_{j-1}} \\ \frac{\partial \varphi_x}{\partial \delta r_{j-1}} & \frac{\partial \varphi_y}{\partial \delta r_{j-1}} & \frac{\partial \varphi_z}{\partial \delta r_{j-1}} \\ \frac{\partial \varphi_x}{\partial \delta r_{j-1}} & \frac{\partial \varphi_y}{\partial \delta r_{j-1}} & \frac{\partial \varphi_z}{\partial \delta r_{j-1}} \end{bmatrix} = F_{j,j-1}$$

(9)

Thus, $M_k$ - covariance matrix of the errors of coordinates of the $k$-point on the well axis should be calculated on the following formula:

$$M_k = (F_{1,1} + F_{2,1}) K_1 (F_{1,1} + F_{2,1})^T + (F_{2,2} + F_{3,2}) K_2 (F_{2,2} + F_{3,2})^T + \cdots + (F_{k-1,k-1} + F_{k,k-1}) K_{k-1} (F_{k-1,k-1} + F_{k,k-1})^T + F_{k,k} K_k F_{k,k}^T .$$

(10)

As azimuths of the intervals are measured relatively to magnetic meridian, which forms the angle $\delta_m$ (magnetic declination) with the geodetic system axis $X^T$, the coordinates $X_k$ are recalculated into geodetic system on formulas:

$$\begin{bmatrix} x_k^I \\ y_k^I \\ z_k^I \end{bmatrix} = \begin{bmatrix} x_k \cos \delta_m - y_k \sin \delta_m \\ y_k \sin \delta_m + y_k \cos \delta_m \\ z_k \end{bmatrix}$$

(11)

Covariance matrix $M^I_k$ of coordinates in geodetic system is calculated by formula

$$M^I_k = A M_k A^T,$$

(12)

where $A$ - matrix of magnetic meridian coordinate system turn to geodetic system, i.e.
The ellipse error elements are calculated on \( M_k \) – covariance matrix of coordinates errors of the every interval end

\[
A = \begin{bmatrix}
\cos \delta M & -\sin \delta M & 0 \\
\sin \delta M & \cos \delta M & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

The ellipse error elements are calculated on \( M_k \) – covariance matrix of coordinates errors of the every interval end

\[
M_k = \begin{bmatrix}
m_x^2 & m_{xy} & m_{xz} \\
m_{xy} & m_y^2 & m_{yz} \\
m_{xz} & m_{yz} & m_z^2
\end{bmatrix}
\]

Then the directional angle \( \theta \) – of error ellipse semi major axis is calculated from the equation

\[
tg 2\theta = \frac{2m_{xy}}{m_x^2 - m_z^2}
\]

And the values \( A \) and \( B \) of semi axes on the following formulas:

\[
A^2 = R + w; \quad B^2 = R - w
\]

where

\[
R = \frac{m_x^2 + m_z^2}{2}; \quad w = \frac{m_{xy}}{\sin 2\theta}
\]

As the error on the axis \( Z \) is loosely correlated with the errors of plane coordinates, the semi axis \( C \) of the semi-axis of the error ellipsoid of the interval end spatial position can be accepted equal to \( m_z \) from the formula (14).

In order for the ellipsoid of errors to correspond to the probability of 0.95, it is necessary to multiply the semi-axes from formula (16) by 2.8 for practical use.

The functions \( f_1(r_{j-1}, r_j) \) in formulas mentioned above (6) depend on the method of increment of coordinates on the measurement interval. The instruction [11] recommends two methods:

- Arithmetic mean;
- Least curvature method.

Foreign references recommend the least curvature method [2], which is on the practical use nowadays.

3. Calculating the probability of combining the uncertainty ellipsoid and the tolerance

The quality measure of the performed well boring is accepted as the combining of the uncertainty ellipsoid with the tolerance area design deviation.

The uncertainty area in well bottom position due to axis interval elements measurements is built on the basis of coordinate errors covariance matrix (formula (14)). Depending on the coordinate dimensions the area can represent the following space:

- Straight line segment – uncertainty along the given direction;
- Ellipse – uncertainty on the section;
- Ellipsoid – uncertainty in 3D – space.

Therefore, it is necessary to determine, what part of ellipsoid is located in the zone of tolerance area. The tolerance area represents the cylinder with circular section of horizontal plane of given radius and height equal to doubled accepted deviation in depth. (Fig. 2 \( \Delta Z_{tol} \) – height tolerance, \( R_{tol} \) – tolerance radius).

The calculations are performed by the method of statistical tests. Within the limits of minimal parralelepiped, containing limited concentration ellipsoid, the points are sporadically generated. There determinate the number \( N \) of points, that came into the ellipsoid, from which there determined \( p \) of points, which are within the tolerance area. Then the relation

\[
q = \frac{p}{N}
\]
Will be the measure of the well bottom proximity to the design position. As it is accepted that \( N = 100000 \), the error will not exceed several tenths of a per cent.

For calculation of uncertain area probability it is necessary to mention the suggestion about the law of error distribution. It is suggested that the error distribution law is normal. In the general case the of probability-density function has a view:

\[
p(\Delta_n) = \frac{1}{(2\pi)^{n/2}|M_n|} e^{-\frac{1}{2} \Delta_n^T M_n^{-1} \Delta_n},
\]

where \( \Delta_n \) -- random dimension vector \( n \); \( M_n \) -- covariance matrix of vector \( \Delta_n \).

If to express the sizes of the field in sigma units (mean square error), then \( P(S_k) \) the probability of the field \( S_k \) is calculated on the formula [14]:

\[
P(S_k) = \frac{\gamma\left(\frac{n+k}{2} \right)}{\Gamma\left(\frac{n}{2} \right)},
\]

Where \( k \)-- is the radius of the field in sigma units;

\( \gamma() \)-- incomplete gamma function

\[
\gamma(s, x) = \int_0^x t^{s-1} e^{-t} dt
\]

\( \Gamma() \)-- the Euler gamma function.

\[
\Gamma(s) = \int_0^\infty t^{s-1} e^{-t} dt
\]

4. Realization of algorithms

The shown algorithms were realized in module “Well bore control” in the program “MG Seti” [15] and tested on oil deposits of Western Siberia. The program allows to perform the basic operations required [1-3], to show the designed and actual position of the well hole (fig. 3a in perspective, 3b in the projection on horizontal plain).

![Figure 3. Designed (white colour) and actual position of well bores.](image)

Determination of well bottom uncertainty ellipse overlapping with the tolerance design area, in fig. 3c is shown in projection on horizontal plane (tolerance area – circle), coefficient of well approaching and many other tasks.

5. Conclusions

The analysis of errors accumulation in determining well bore uncertainty ellipsoid with the use of different estimation methods [2, 12] showed that the calculation without taking into account the correlation of adjacent intervals underrates the final error, that is, the size of uncertainty ellipsoid by 20 – 40%.
Different variants of tolerance area determination, in table view or in view of empirical dependences, [11,12, 16] should be determined for a particular deposit or a group of deposits with similar mountainous and geological conditions.

The accuracy increase of well boring and mining inclinometric control requires the accuracy increase of telemetric and inclinometric devices in measuring zenith angle and especially azimuth.

6. References

[1] Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) https://www.iscwsa.net
[2] Introduction to Wellbore Positioning 2017 This version is V09.10.2017 This eBook and all subsequent revisions will be hosted at: http://www.uhi.ac.uk/en/research-enterprise/energy/wellbore-positioning-download 247 p
[3] Society of Petroleum Engineers (SPE) www.spe.org
[4] ISCWSA: WELL INTERCEPT SUB-COMMITTEE EBOOK 2019 This eBook and all subsequent revisions will be hosted at: http://www.uhi.ac.uk/en/research-enterprise/energy/wellbore-positioning-download 2019 107 p
[5] Ekseth R, Kovalenko K, Weston J L, Torkildsen T, Nyrnes E, Brooks A, Wilson H 2006 The Reliability Problem Related to Directional Survey Data Paper SPE 103734 presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition (Bangkok, Thailand) 13–15 November 2006 doi: 10.2118/103734MS
[6] Ekseth R, Torkildsen T, Brooks A, Weston J, Nyrnes E, Wilson H, Kovalenko K 2010 High Integrity wellbore Surveying December 2010 SPE Drilling and Completion, SPE133417
[7] Nyrnes E, Torkildsen T 2005 Analysis of the Accuracy and Reliability of Magnetic Directional Surveys Paper SPE 96211 presented at the SPE/IADC Middle East Drilling Technology Conference and Exhibition (Dubai) doi: 10.2118/96211-MS
[8] Nyrnes E, Torkildsen T, Haarstad I, Nahavandchi H 2005 Error Properties of Magnetic Surveying Data. Paper presented at the SPWLA 46th Annual Logging Symposium (New Orleans)
[9] Torkildsen T, Harvardstein S T, Weston J, Ekseth R 2008 Prediction of Wellbore Position Accuracy When Surveyed With Gyroscopic Tools Paper SPE 90408, SPE Drilling and Completion
[10] Ekseth R, Weston J, Ledroz A, Smart B, Ekseth A 2011 Improving the Quality of Ellipse of Uncertainty Calculations in Gyro Surveys to Reduce the Risk of Hazardous Events like Blowouts or Missing Potential Production through Incorrect Wellbore Placement Paper SPE 140192 presented at SPE/IADC Drilling Conference (Amsterdam)
[11] 1989 The instructions for inclinometricheskaya research in well bores (Kalinin: NPO «SojuzPromGeofizika») 14 p
[12] Kashnikov Ju A, Beljaev K V, Bogdanec E S, Sogorin A A 2018 Mining support of oil and gas deposits development (M.: OOO «Izdatel'skij dom Nedra») 454 p
[13] 2018 Methodological guidelines “Directional drilling” № P2-10 M-0038 VERSJJa 1.00. Vvedeny v deystvie Raspoporazheniem OOO «RN-Juganskneftegaz» № 2126
[14] Korn G, Korn T 1974 Spravochnik po matematike (dlja nauchnyh rabotnikov i inzhenerov) [handbook of mathematics (for scientists and engineers)] (M) 832 p
[15] Program complex “Mining and geodetic networks and survey” https://sholomitskij.wixsite.com/sholomitskij/mgseti
[16] Absimetov V E, Solovev D B 2020 The Use of Effective Design Solutions and High-Tech Building Materials for Reconstructing Residential Buildings of Mass Development in 1960-1990 IOP Conf. Ser.: Mater. Sci. Eng. 753 Paper № 032027. [Online]. Available: https://doi.org/10.1088/1757-899X/753/3/032027