DOI: https://doi.org/10.26642/ten-2024-1(93)-406-414
UDC 622.1

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Angular measurement errors in underground mine surveying reference networks

Surveyor's reference networks are the main geometric basis of all underground surveys and consist of polygonometric courses laid, as a rule, along capital and main mine workings.

When laying polygons along mine workings, horizontal angles between each two adjacent sides of the course, inclination angles and lengths of the course sides are measured. Each measurement is performed with some error, which eventually leads to errors in determining the coordinates of polygon points. The peculiarities of underground polygonometric courses due to their forced configuration determined by mine workings, the presence of forced short sides and a limited number of starting points, contribute to the rapid accumulation of errors in the course as the distance from the starting points.

The accuracy of measurements in the polygonometric passes, laid in the construction of underground reference networks, is characterized by the general normative indicators: the mean square error of measurement of horizontal angles of 20", vertical angles – 30".

According to the requirements of the current normative instructions, the measurement of angles in underground polygonometric passages should be made with theodolites of T15 type or theodolites with the accuracy of the reference device not less than 15". The last requirement applies to theodolites of T30 type.

In polygonometric moves laid along the mine workings with an angle of inclination of less than 30 °, the angles are measured in one repetition or reception.

Measurement of angles in mine workings with an inclination angle of more than 30 ° is recommended to perform a method of techniques (at least two), observing the following rule: before each technique set the vertical axis of rotation of the theodolite in a plumb position and re-centering the device.

If we proceed only from the instrumental component of the total error of angle measurement to ensure the mean square error of horizontal angle measurement ±20" theodolite type T15 should perform angle measurement in one full method, and theodolite T30 – in three methods.

Instrumental error of angle measurement is caused by errors of sighting, counting, eccentricity of the limb and alidade, incorrect geometry of the horizontal circle, non-verticality of the theodolite rotation axis.

The studies of errors in measuring horizontal angles in underground surveyor's polygonometric courses made it possible to draw the following conclusions:

– the recommendations of the instruction «Surveying work at coal mines and surface mines» on the use of theodolites with a readout accuracy of 15" does not provide the required accuracy of horizontal angle measurements;

– when using theodolites of T15 type to measure the angle with sides up to 20 m it is necessary to use only automatic centering of theodolite and signals;

The scientific paper contains charts for determining the ways of centering and the number of methods of measuring horizontal angles in underground surveyor's polygonometric moves.

Keywords: *underground surveyor's polygonometric passages; accuracy of horizontal angles measurement; centering method; number of techniques.*

Introduction. Any measurements are always accompanied by errors, i.e. deviations of measured values from their true values. Improvement of measurement techniques and designs of measuring instruments and devices, improvement of observer's qualification can increase the accuracy of measurements, i.e. reduce deviations of the results obtained from their true values. It is impossible to obtain absolutely error-free measurement results. Therefore, in practice, measurements are made in such a way that the results are obtained with some specified accuracy. The notion of specified accuracy should be accompanied by certain numerical criteria, which should represent a probabilistic characteristic of possible deviations of obtained results of measurement processing from their true values.

Establishment of these criteria, development of methods of their obtaining and estimation are among the tasks of the theory of measurement errors.

The main questions and a number of private questions considered in the theory of measurement errors can be formulated as follows:

1) study of laws of occurrence and distribution of measurement and calculation errors;

2) establishment of tolerances, i.e. criteria indicating the presence of inadmissible deviations of measurement results (gross errors);

3) finding the most accurate probability value of the determined quantity from the results of its repeated measurements;

4) precalculation of the expected accuracy and assessment of the accuracy of the obtained measurement results;

5) characterization of the final values accuracy of the determined quantities according to the results of mathematical measurement processing.

All quantities, which are dealt with in surveying, can be divided into *measured*, approximate values of which are obtained as a result of measurements, and *calculated*, i.e. found by calculations as a function of the measured values.

The measurement of a quantity is understood as its comparison with a quantity homogeneous to it, accepted as a unit of measure. This comparison is usually made by performing a number of operations, often quite complex. Such a number of operations include standardization of the measuring instrument, sighting, matching of indices, production of readings, etc. The result of a measurement is understood to be the final result obtained as a result of all operations.

In order to detect blunders, as well as to improve the accuracy of the results, measurements in surveying are always repeated.

According to the accuracy of the measurement, results are divided into equally accurate and unequally accurate.

Equivalent means homogeneous results obtained by measurements with the same instrument (or with different instruments of the same accuracy class), by the same or equivalent methods, by the same number of techniques and under the same conditions.

Measurement results are called unequal if the specified conditions of equality are not met.

Examples of equally accurate measurements are:

1) measurement of horizontal or vertical angles by theodolites of the same accuracy, by the same method and by the same number of techniques; angles in polygonometric courses of the same class are measured with equal accuracy;

2) measuring the length of a line with the same measuring instrument, in the same way;

3) measurement of the temperature of the air or measuring device with a thermometer of the same construction and accuracy.

Note that the last example involves the measurement of a variable quantity, so the measurement results must be attributed to specific points in time.

Examples of unequal measurements are:

1) measuring angles by the same method and number of techniques, but with instruments of different accuracy;

2) measuring angles in the same way, with the same tools, but with a different number of steps;

3) measuring the length of a line with measuring instruments of different accuracy, for example, a 10-meter braid tape measure and a 30-meter steel tape measure.

In terms of accuracy, only measurements of homogeneous quantities, i.e. identically named quantities, can be compared with each other.

The concepts of necessary and redundant measured values are important in the issues of mathematical processing of measurements.

To solve surveying tasks, it is usually necessary to measure several quantities. For example, in order to solve a problem on the terrain of surveying the axes of a shaft or other engineering structure, it is necessary to measure some minimum values.

The number of measured quantities minimally necessary for solving the task is called the number of necessary quantities; it is often called the number of necessary measurements.

The difference between the number of all measured values and the number of required values is called the number of redundant values or the number of redundant measurements.

In surveying works redundant measured values are obligatory: they allow detecting errors in measurements and calculations and increasing the accuracy of the results, determining the desired values.

When measuring one quantity, one measurement is required, the rest are redundant.

Analytical substantiation of occurrence of measurement errors. As stated above, any measurement is accompanied by errors, i.e. deviations of measurement results from the true values of the measured quantities.

What is the cause of these errors?

The measurement process involves the observer, instruments and devices, and the external environment. This whole complex of conditions is constantly changing and it is impossible to take into account these changes without error. Therefore, the measurement results deviate from the true values, and each time in a different way.

Let us call the totality of factors influencing the measurement results (measurement object, observer, instruments and devices, external environment) the measurement conditions. We can say that fluctuations of the measurement results reflect continuous changes of the measurement conditions.

To study the properties (regularities of occurrence) of measurement errors, it is most expedient to use the true values of measured quantities. We can accept as true the value of the measured quantity known to us with high accuracy, i.e. with negligibly small error compared to the errors of the measurements themselves. Some functions of measured quantities can be known to us and determined without error (for example, the sum of angles in a triangle). Let us denote the true value of the measured quantity by X, the result of measurement by xi. The difference between the measurement results and the true values, in the sense of «measured minus true» or «what is minus what should be», is called the true measurement error Δ, i.e., the true measurement error Δ.

$$\Delta = x_i - X. \quad (1)$$

When we have true errors in large numbers, we can study the regularities of their occurrence. However, in most cases, from the point of view of practice, the true value of the measured quantity and, consequently, the true errors remain unknown. Therefore, to study the properties of measurement errors, indirect methods of research are more often used, for example, studying the laws of distribution of measurement results and laws of distribution of inconsistencies.

The causes of unavoidable measurement errors are:

– influence of external conditions;
– inaccuracies of manufacturing and alignment of instruments and devices;
– inaccuracies in the performance of operations by the observer;
– continuous changes in all these measurement conditions.

In its turn, each of the mentioned sources of errors is the result of influence of many factors. At that, each of these factors has a small influence on the measurement result in comparison with the total influence of all factors. Thus, for example, the following sources of errors influence the result of horizontal direction measurement in the mine workings: multiple refraction of rays coming from the sighting signal to the observer's eye, insufficient and uneven illumination of the sighting object, instability of the signal, instability of the theodolite on the tripod and in the lifting screws, temperature and other changes in the instrument, errors of instrument alignment, errors of horizontal circle separation, errors of the reference fixture, personal errors of the observer during sighting and measurement.

Each of these sources of error generally has a small effect on the final result compared to the combined effect of all sources and varies in its effect from reception to repetition.

In turn, each of these error sources can be subdivided into a number of smaller sources. For example, instrument alignment error is subdivided into collimation error, horizontal axis tilt error, vertical axis tilt error, instrument leveling error, etc.

Thus, the deviation of the measured value from the exact value is the result of a large number of causes. Each of the causes, in case of high-precision measurements, has negligible effect on the result of a single measurement compared to the total influence of all causes.

According to the sources of occurrence, measurement errors are divided into *instrumental, external, or environmental, and personal errors*.

This classification is of great importance for disciplines studying instruments and measurement methods. For the theory of errors, it is of minor importance. A significant role in the error theory belongs to the classification of errors according to the regularities of their occurrence.

Rough errors. The theory of mathematical processing of measurements does not consider gross errors caused by blunders or miscalculations of the observer, malfunctions of instruments and devices, sharp deterioration of external conditions, etc. The theory of mathematical processing of measurements does not consider gross errors. Measurement results containing gross errors should be identified and discarded.

Random and systematic errors. Two main categories of errors are distinguished from the set of elementary errors that make up the total measurement error: random and systematic errors. Since elementary errors, as a rule, change their magnitude when measurements are repeated, they can be considered as values of random quantities.

Random are elementary errors that represent values of random variables with mathematical expectation negligibly different from zero.

Systematic errors are elementary errors representing values of random variables with mathematical expectations differing markedly from zero.

Systematic errors can be constant, i.e. those that retain both sign (direction) and magnitude during measurements.

The sources of random errors are always much more numerous than systematic errors, but the effect of each of them is usually small. In high-precision measurements, the main attention should be paid to combating the influence of systematic errors. Here we will give just a few examples of systematic errors for illustration purposes.

1. Errors in the measured value of the line length on the ground due to deviation of the measuring tape from the gauge.

2. Error in determining the length of the measuring tape (comparing error). This error is constant and acts in proportion to the measured distance.

3. Systematic errors of the theodolite limb dashing. At permutations of the limb these errors acquire a periodic character and their influence on the average value of angle measurement techniques is weakened to a great extent.

4. Errors in determining corrections for the temperature of the measuring steel tape located on the ground. Usually, the air temperature is measured and taken as the temperature of the strip, thus allowing a systematic error in the correction for the temperature of the strip. Such errors are called one-sided errors.

Examples of random errors include the error of readout on the angle gauge circle; part of the sighting error due to image fluctuations; random errors in applying the strokes of the limb; the effect of signal vibration; errors of readout on the leveling stake; errors for rounding off numbers in calculations and counting on scales, etc.

Analysis of the latest research and publications. The analysis of normative base [1, 2], modern educational and scientific literature on the issues of ensuring the specified accuracy of the underground surveying reference network [3–8] indicated the need to justify the method of measuring the horizontal angle and the number of receptions or repetitions. This task arises because of the wide variety of specifications. In fact, each mining operation is unique and so is the location of reference network points in it. The same ambiguous solutions requiring a qualified approach and certain labor input on the part of the performer are given in foreign works [9, 10].

The accuracy of measurements in polygonometric passes, laid during the construction of underground reference networks, is characterized by general normative indicators [1, 2], shown in Table 1.

Table 1

Requirements of the instructions regarding the accuracy of reference networks

Mean square error of angle measurement		Mean square error of angle measurement Coefficients of random (μ) and systematic (λ) influence at linear measurements with tape measure in excavations with inclination angles			
		less than 15°		more than 15°	
horizontal	vertical	μ	λ	μ	λ
20"	30"	0,0005	0,00005	0,0015	0,0001

According to the requirements of the current normative instructions, measurement of angles in underground polygonometric passages should be made by theodolites of T15 type [1] or theodolites with the accuracy of the reference fixture not less than 15" [2]. The last requirement applies to theodolites of T30 type.

The purpose of this work was to study the accuracy of angular measurements depending on the method of centering and mining conditions of mine workings to ensure a given accuracy of creating underground reference surveying networks, which is an urgent applied task at mining enterprise.

Presentation of the main material. In the polygonometric runs, laid along mine workings with an angle of inclination of less than 30 °, the angles are measured by a single repetition or reception.

Using the measurement of angles in mine workings with an inclination angle of more than 30 °, it is recommended to perform a method of techniques (at least two), observing the following rule: before each technique set the vertical axis of rotation of the theodolite in a plumb position and re-centering the device.

If we proceed only from the instrumental component of the total error of angle measurement to ensure the mean square error of horizontal angle measurement ±20" theodolite type T15 should perform angle measurement in one full method, and theodolite T30 – in three methods.

Instrumental error of angle measurement is caused by errors of sighting, counting, eccentricity of the limb and alidade, incorrect geometry of the horizontal circle, non-verticality of the theodolite rotation axis.

In the total error of angle measurement there is also a component caused by the centering error of the theodolite and signals. The average error of horizontal angle measurement due to inaccuracy of centering of the theodolite and signals is composed of three separate errors:

m_{c_A} – average angle measurement error due to inaccuracy of centering of signal A;

m_{c_B} – average angle measurement error due to inaccurate centering of signal B;

m_e – average angle measurement error due to inaccurate centering of the theodolite.

$$m_{c_A} = \pm\sqrt{m_{c_A}^2 + m_{c_B}^2 + m_e^2}. \tag{2}$$

Expressions for calculating the errors of horizontal angle measurement due to inaccuracy of centering signals are as follows:

$$m_{c_A}^2 = \rho^2 \frac{e_A^2}{2b^2}\,; \qquad m_{c_B}^2 = \rho^2 \frac{e_B^2}{2a^2}. \tag{3}$$

The error m_e is calculated by the formula:

$$m_e^2 = \frac{\rho^2 e^2}{2a^2 b^2}(a^2 + b^2 - 2ab\cos\beta). \tag{4}$$

In the final form, taking into account that the methods and, consequently, the centering errors of both signals are the same, the horizontal angle measurement error due to the inaccuracy of centering of the theodolite and signals can be calculated by the formula:

$$m_{ц_i} = \pm\sqrt{\frac{\rho^2}{2a^2b^2}\left[e_C^2(a^2+b^2)+e^2(a^2+b^2-2ab\cos\beta)\right]}. \tag{5}$$

The analysis of the above formula allows us to draw the following main conclusions:

1. The influence of the error of centering signals on the error of angle measurement does not depend on its magnitude and is inversely proportional to the length of the sides forming the angle.
2. The influence of the theodolite centering error on the error of angle measurement depends on its magnitude. The greatest influence of the theodolite centering error (all other things being equal) will have the greatest impact when measuring angles close to 180°.
3. The effect of the theodolite centering error is inversely proportional to the length of the sides forming the angle.
4. The effect of centering error of the theodolite and signals is greater than the difference between the lengths of the sides of the measured angle.

In underground surveys prevail the most unfavorable conditions for measuring the horizontal angle, because most of the angles of underground polygons close to 180 °, and the sides of the angles are not so large and often sharply differ from each other in length. This requires special attention to the centering of signals by theodolites.

According to [1, 2], the method of centering the theodolite and signals is chosen depending on the lengths of the sides of the measured angle in accordance with Table 2.

Table 2

Theodolite and signal centering accuracy

Horizontal extent of the smaller side of the angle, m	Centering method
Up to 10	Automatic centering
10...20	Optical centering or double angle measurement with independent centering with cord plummet before each measurement
Over 20	Single centering with cord plummet

Many studies have resulted in estimates of the linear errors of theodolite centering and signal (e and e_c), which are used to evaluate the results of angular measurements [3]:

– single centering with cord plummet......,,,,,,. 1,2–2,0 mm;
– optical centering... 0,8–1,2 mm;
– automatic centering..........................,,,....... 0,5–0,8 mm.

In conditions of underground mine workings, where points of theodolite tracks are fixed in the roof of mine workings, optical centering is practically not applied. In the overwhelming majority of cases the theodolite is centered by a cord plummet, and sighting is carried out directly on plumb bobs fixed on the rear and front points of the course. However, this does not exclude the presence of centering error at the sighting points, because the center of the point of the underground reference network is fixed by a hole with a diameter of 2 mm [1, 2], which provides free displacement of the cord plummet from the center of the point by the value $e_c = R - r$, where R is the radius of the center hole, equal to 1 mm; r is the radius of the cord plummet (we take equal to 0,2 mm). Thus, e_c = 0,8 mm.

Thus, three variants of the influence of centering errors on the error of measuring horizontal angles in mine workings can be considered:

– angle measurement is carried out according to the three-state scheme with centering of the theodolite and signals by a cord plummet (we take $m_{c_A} = m_{c_B} = m_e$ = 1,5 mm);

– centering of the theodolite is carried out by a cord plummet (m_e = 1,5 mm), sighting – directly on the plummet ($m_{c_A} = m_{c_B}$= 0,8 mm);

– angles are measured by three-state scheme with automatic centering of theodolite and signals ($m_{c_A} = m_{c_B} =$ $= m_e$ = 0,8 mm).

The total mean square error of horizontal angle measurement is determined by the formula:

$$m_\beta = \pm\sqrt{m_i^2 + m_{ц_i}^2}. \tag{6}$$

Tables 3–5 show the results of calculations of errors of measurement of horizontal angle by the theodolite T15 with different methods of centering the theodolite. Figures 1–3 show visualization of the calculations of horizontal angle measurement errors for different ways of centering the theodolite and signals.

Table 3

Errors of horizontal angle measurement at $m_{c_A} = m_{c_B} = m_e$ *= 1,5 mm*

Length of angle side to signal B, mm	Horizontal angle measurement error, sec.					
	Length of the side of the angle before signal A, mm					
	1000	20000	40000	60000	80000	100000
1000	536	318	314	312	312	311
20000	318	31	25	24	23	23
40000	314	25	20	19	18	18
60000	312	24	19	17	17	17
80000	312	23	18	17	16	16
100000	311	23	18	17	16	16

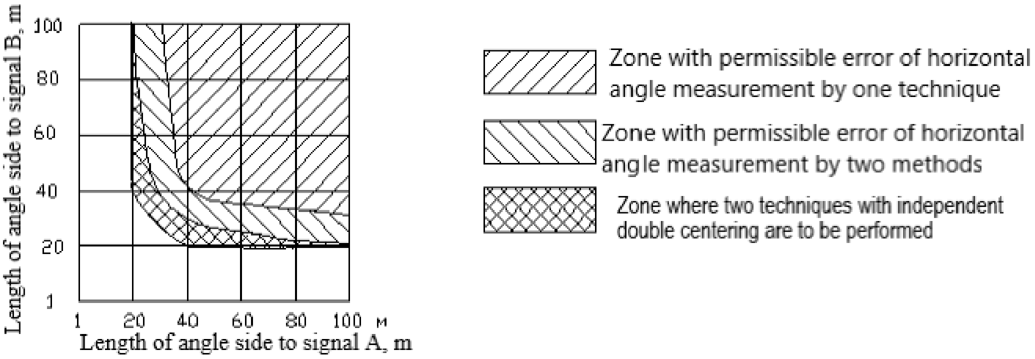

Fig. 1. Error field of horizontal angle measurement by theodolite T15 at theodolite centering error and signal 1,5 mm

Table 4

Angle measurement errors at m_e *= 1,5 mm;* $m_{c_A} = m_{c_B}$ *= 0,8 mm*

Length of angle side to signal B, mm	Horizontal angle measurement error, sec.					
	Length of the side of the angle before signal A, mm					
	1000	20000	40000	60000	80000	100000
1000	468	258	253	252	251	250
20000	258	28	23	22	21	21
40000	253	23	19	18	17	17
60000	252	22	18	17	16	16
80000	251	21	17	16	16	16
100000	250	21	17	16	16	16

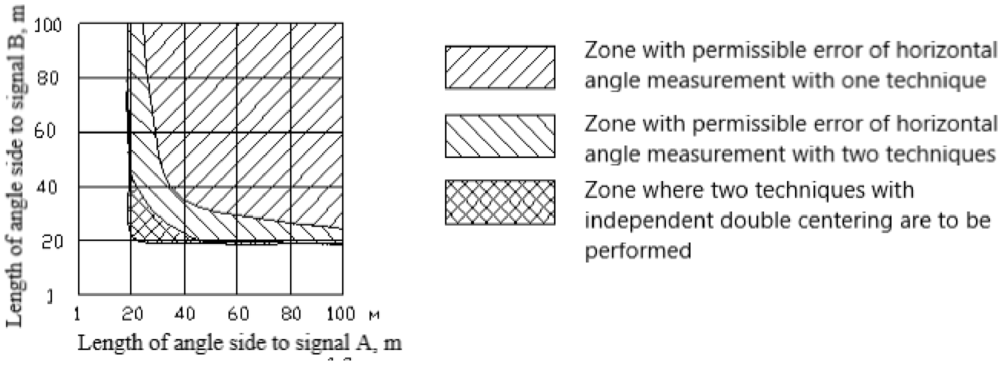

Fig. 2. Error field of horizontal angle measurement with theodolite T15 at theodolite centering error of 1,5 mm and signal centering error of 0,8 mm

Table 5

Angle measurement errors at $m_{c_A} = m_{c_B} = m_e$ = 0,8 mm

Length of angle side to signal B, mm	Horizontal angle measurement error, sec.					
	Length of the side of the angle before signal A, mm					
	1000	20000	40000	60000	80000	100000
1000	286	170	168	167	167	167
20000	170	21	19	18	18	18
40000	168	19	17	16	16	16
60000	167	18	16	16	16	15
80000	167	18	16	16	15	15
100000	167	18	16	15	15	15

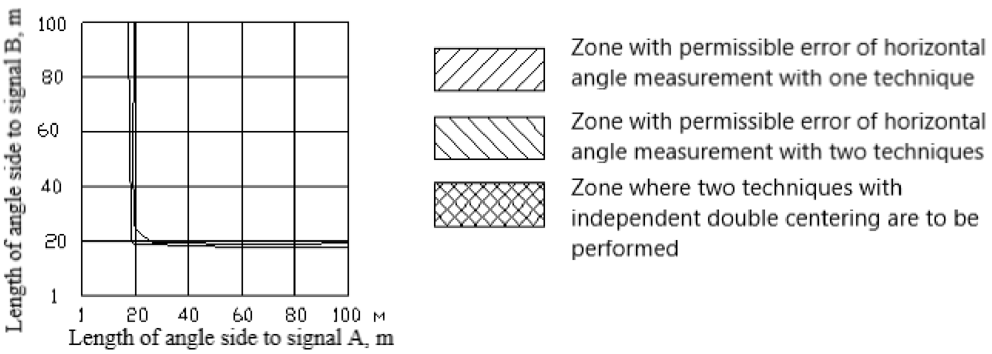

Fig. 3. Error field of horizontal angle measurement by theodolite T15 at theodolite centering error and signal 0,8 mm

The instrumental error of angle measurement can be reduced by increasing the number of measurement techniques, and the error caused by inaccurate centering of the theodolite – by re-centering.

The results of error analysis corresponding to different methods of angle measurement with theodolite T15 are shown in the figure.

Conclusions.

1. Recommendations of the instruction «Surveying work at coal mines and surface mines» on the use of theodolites with a readout accuracy of 15" does not provide the required accuracy of horizontal angle measurements.

2. When using theodolites of T15 type for angle measurement with sides up to 20 m, it is necessary to use only automatic centering of theodolite and signals.

3. When measuring angles with centering by cord plumb bob, the method of angle measurement should be chosen in accordance with the graph of the error field.

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Research interests:

– rock mass shear and deformation;
– surveying devices and technologies;
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Похибки кутових вимірювань у підземних маркшейдерських опорних мережах

Маркшейдерські опорні мережі є головною геометричною основою всіх підземних зйомок і складаються з полігонометричних ходів, що прокладаються, як правило, капітальними та основними гірничими виробками.

Під час прокладання полігонів по виробках вимірюють горизонтальні кути між кожними двома суміжними сторонами ходу, кути нахилу і довжини сторін ходу. Кожне вимірювання виконується з якоюсь похибкою, що в підсумку призводить до помилок визначення координат пунктів полігонів. Особливості підземних полігонометричних ходів зумовлені їхньою вимушеною конфігурацією, яку визначають гірничі виробки, наявністю вимушено коротких сторін і обмеженим числом вихідних пунктів, сприяють швидкому накопиченню помилок у ходах у міру віддалення від вихідних пунктів.

Точність вимірювань у полігонометричних ходах, що прокладаються під час побудови підземних опорних мереж, характеризується загальними нормативними показниками: середня квадратична похибка вимірювання горизонтальних кутів – 20", вертикальних кутів – 30".

Згідно з вимогами чинних нормативних інструкцій вимірювання кутів у підземних полігонометричних ходах має проводитися теодолітами типу Т15 або теодолітами з точністю відлікового пристосування не менше 15". Остання вимога стосується теодолітів типу Т30.

У полігонометричних ходах, що прокладаються виробками з кутом нахилу менше 30°, кути вимірюють одним повторенням або прийомом.

Вимірювання кутів у виробках із кутом нахилу понад 30° рекомендується виконувати способом прийомів (не менше ніж два), дотримуючись такого правила: перед кожним прийомом встановлюють вертикальну вісь обертання теодоліта у прямовисне положення і повторно центрують прилад.

Якщо виходити тільки з інструментальної складової загальної похибки вимірювання кута для забезпечення середньої квадратичної похибки вимірювання горизонтального кута ±20" теодолітом типу Т15 необхідно виконати вимірювання кута одним повним прийомом, а теодолітом Т30 – трьома прийомами.

Інструментальна похибка вимірювання кута зумовлена помилками візування, відлічування, ексцентриситету лімба й алідади, рену, неправильної геометрії горизонтального кола, невертикальністю осі обертання теодоліта.

Виконані в роботі дослідження похибок вимірювання горизонтальних кутів у підземних маркшейдерських полігонометричних ходах дозволили зробити такі висновки:

– рекомендації діючої інструкції з використання теодолітів з точністю відліковування 15" не забезпечує необхідну точність вимірювань горизонтального кута;

– у разі використання теодолітів типу Т15 для вимірювання кута зі сторонами до 20 м варто застосовувати винятково автоматичне центрування теодоліта і сигналів.

У науковій роботі наводяться графіки для визначення способів центрування та кількості прийомів вимірювання горизонтальних кутів у підземних маркшейдерських полігонометричних ходах.

Ключові слова: підземні маркшейдерські полігонометричні ходи; точність вимірювання горизонтальних кутів; спосіб центрування; кількість прийомів.

The article was sent to the editorial board on 18.04.2024.