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MINING SURVEYING

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1 INTRODUCCION

Mine surveying is a traditional scientific discipline implemented at VSB-TU Ostrava since 1907, as the only university in the Czech Republic. For mining activities, the field is specialised in the preparation of mine maps, delineation of mine workings, keeping an account of mineral reserves in the deposit, a compilation of documents for planning mine exploration, preparation and mining works and monitoring and evaluation of the impact of mining operations on structures on the surface and in the mine. The field Mine Surveying is, therefore, fully linked to mining operations in mines and quarries and requires knowledge of surveying methods and experience and knowledge of these operations. For mining activities (excavation of pits, shafts, adits, tunnels and other underground spaces, rehabilitation of underground spaces, the opening of caves and mining of unreserved minerals), the field specializes in the preparation of documents for their design, delineation, guidance in their implementation and preparation of documentation of their actual implementation. Currently, it includes all measurements, spatial data collection and calculations for the production of information systems and the creation of maps that are used to identify and document information in all stages of mining activities and activities carried out using mining methods both underground and on the surface: prospecting and exploring mineral deposits (Geology, Geoinformatics), mining and exploitation of minerals (Mining, Geotechnics, Underground Construction), remediation and reclamation (Environmental Protection). The field Mine Surveying deals with collecting, evaluating, and interpreting spatial data with the required accuracy and the influences affecting this accuracy.

In the preparation of study materials, we have drawn on existing textbooks, specialized domestic and foreign literature, legislation and trends applicable at the time of their creation. The study material focuses on new mining measurement methods and procedures developed in the Department and does not cover the entire discipline. It builds on the knowledge and skills acquired through the study of surveying.

2 CONNECTING SURVEYS AND ORIENTATION MEASUREMENTS

Connecting surveys and orientation measurements have been and still are the fundamental and the most difficult tasks in mine surveying, whose purpose is to determine the coordinates of the points on the basic orientation line on the connected horizon in the same coordinate system as is used on the surface. This basically consists in transferring the coordinate system used to survey the situation on the surface to the underground. The basic orientation line, whose coordinates and bearings are determined based on the connecting surveys and orientation measurements, is then used to define the basic underground control in the same coordinate system as structures on the surface, allowing to determine the mutual position of the underground mining works in an underground mine or an underground horizon and the structures on the surface, mining works in a mining area or in the mining areas of neighbouring mines. The knowledge of the mutual position of the structures on the surface and underground mining works is essential for protecting structures on the surface against the impacts of exploitation and for designing and implementing safety measures aimed at their protection. Such information is used to determine protective pillars which protect industrial facilities, rivers, roads and the mine outlets both in one mining area and in neighbouring mining areas. The determination of the accurate position of underground mining works thus has relevance not only to mining and technical solutions but also to the solutions designed to enhance safety and environmental protection.

As the purpose of such surveys and measurements is to determine the mutual orientation of the situation in a mine in relation to the situation on the surface, this type of measurements is referred to as “orientation measurements” in some countries.

The principle of connecting surveys and orientation measurements and the possible methods of performing them is described in detail in Chapter 3 of this study and is based on the findings stated in the publications of the following authors: prof. Ing. Dr. Techn. František Köhler, prof. Ing., Dr. mont. František Čechura, DrSc., prof. Ing. Aleš Mučka, DrSc., prof. Ing. Jirí Matouš, CSc. and, primarily, prof. Ing. Dr. mont. Karel Neset, DrSc.

In his scientific and expert study, Prof. Köhler dealt with the improvement of surveying techniques [12] and instruments and is known to the specialists in the field mainly for his improvement of prof. Fuhrmann's shaft plumbing photoplummet (pendulum) manufactured by Hildebrand. The principle is described in [11]. New methods of mine surveying as applied to underground roadways and orientation measurements using a gyrotheodolite [19], including the accuracy of orientation measurements performed by means of two vertical shafts and a gyrotheodolite [18] were addressed by prof. Mučka in his scientific work at the Mine Surveying Department in 1958 – 1991. Prof. Matouš focused primarily on the impacts of undermining and on surveying instruments. However, connecting surveys and orientation measurements are elaborated in greatest detail in the publication by prof. Neset: *Důlní měřictví II, Měření výškové, připojovací a usměrňovací, měření vytyčovací* (1967, [25]) (in English: *Mine Surveying II, Connecting Surveys and Altimetric, Orientation and Setting Out Measurements*).

Connecting surveys and orientation measurements are treated briefly in [9]; however, the publication focuses rather on mining engineering. One whole chapter is devoted to “Mine Surveying” in [6], which also includes the basic mine surveying terminology. The author outlines a proposal for defining and stabilising the basic underground control points and measuring angles and depths in mines, and ultimately gives a brief description of the principle of connecting surveys (Weisbach method) and orientation and depth measurements. The chapter also lays down the principle of orientation measurements by means of a gyrotheodolite.

The methods of conducting connecting surveys and orientation measurements are also presented in [31]. The study describes the basic principle and states that “mining orientation” can be performed using geometric, optical and gyroscopic methods. According to the author, three geometric methods can be applied depending on the type of the underground work exploitation:

- through an adit entrance or pitch mining work by continuing a traverse line from the points on the surface of the Earth;
- by means of one shaft (vertical shaft), when two plummets are lowered in the shaft, creating a vertical projection datum; this method consists in determining the geometric relations between the points on the surface and those in the shaft or, more precisely, on the connected horizon;
- by means of two vertical shafts (pits) connected by mine exploitation, when a plummet is lowered in each pit; this method consists in determining the coordinates on the surface and surveying the traverse between the plummets so lowered.

According to the author [31], the optical method consists in the orientation by means of a vertical sight line. Magnetic orientation is performed using instruments with a declination needle, such as compasses and declinatoriums. However, due to the fast development of surveying instruments, these methods have already become too obsolete. Gyroscopic orientation, as the author puts it, the most advanced method of “orientation” of underground mining works, is based on the ability of a gyrotheodolite to stabilise its axis in the direction (plane) of the astronomical meridian.

Publication [26] states that classical methods of conducting connecting surveys, e.g., by means of a traverse, cannot be used in extremely deep pits as the projection of the coordinate system on the surface to the connected horizon is performed as a separate projection of the position and the bearing. The author says

that the position of underground mining works and structures on the surface and on the connected horizons of the underground mining works can be determined mechanically and optically; however, orientation is often measured with the help of very accurate gyrotheodolites. Nevertheless, the author sees a problem in this orientation measurement method in that it is often influenced by deflections of the gyrotheodolite from the plumb line, which are not known in advance. The paper describes the application of a new method of determining the bearing by a combination of autocollimation and the very accurate inertial navigation system (INS). The INS consists of three gyroscopes and three accelerometers, which are deflected from each other in three perpendicular directions. The results obtained through measurements using the INS are compared with those obtained using the GYROMAT 2000 gyrotheodolite. The author concludes that the accuracy of the INS is comparable with GYROMAT 2000.

The issue of inertial measurements of geodetic quantities is dealt with in [17]. In inertial surveying, the term “gyroscoping” means levelling the system and its orientation to the north using gyroscopes and, primarily, accelerometers. “Gyrocompass” then means a set of these sensors.

The position and height connection of an underground geodetic network to the surface network is dealt with in connection with the construction of the largest accelerator of sub-atomic particles, the Superconducting Super Collider (SSC). The SSC was built and financed by the U.S. Department of Energy and is situated near Waxahachie, 40km south of Dallas [33]. The device has a nominal diameter of 4.2 m, is 87 km long and is placed 20–80 m underground. Additional components and facilities necessary for operating the SCC, e.g., such as ventilation, are placed in cut-and-cover excavation tunnels extending another 37 km. The SSC is connected to the surface by clusters of a total of 45 vertical shafts which provide access for personnel, ventilation and other equipment and are located at intervals of approximately 4.4 km. The main tunnel had to be positioned, in the horizontal and vertical dimensions, with a tolerance of ± 8 inches (0.2 m) of the designed location.

The resulting tolerance for the surveying control was ± 3 inches (0.076 m) at the selected level of confidence of $\alpha=0.01$, which means a 99% risk (probability) that the value of a random quantity will exceed the confidence interval. The tolerance for the relative vertical positioning was ± 0.5 inches (0.012 m), which was the accuracy required for running in the final tunnel vault. For these purposes, a surface control network was provided by GNSS technology using very precise ephemeris. The network was designed to yield a maximum relative horizontal positional accuracy across the SCC ring of ± 0.015 m at the level of confidence of $\alpha=0.01$ and was stabilised by massive concrete monuments. The network consisted of 22 points which served, among other things, as calibration lines for gyrotheodolites and electronic distance measurement (EDM) instruments. The vertical control network consisted of 130 deep benchmarks, which were stabilised in competent bedrock. The method of connecting the underground control to the surface control is shown in Fig. 1. The horizontal control transfer was achieved using the Weissbach method with the Taylor Hobson Spheres. The Taylor Hobson Spheres are also known as DISTINVAR (invar measuring device) and are used for measuring displacements and deformations of dams, as described in [28]. The connecting surveys were performed from points located approx. 40 m of the pit bank.

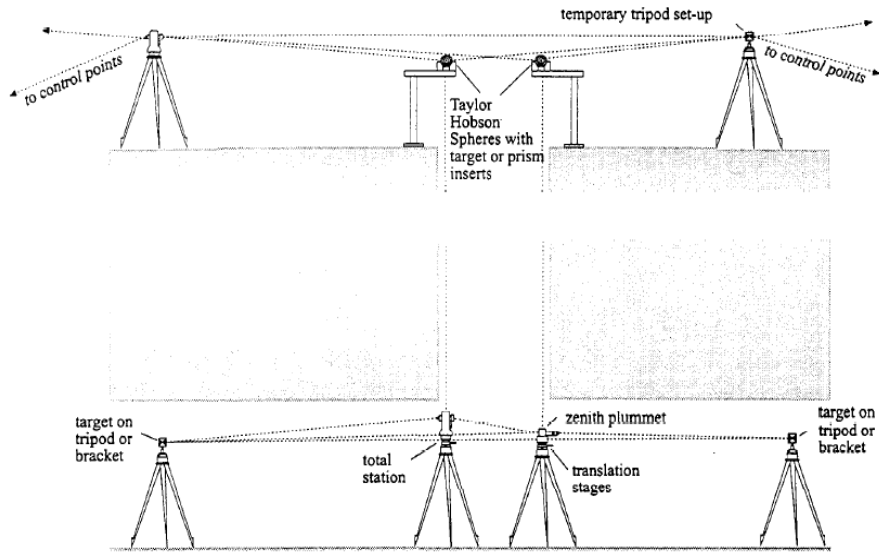


Fig. 1 Transfer of SSC's underground horizontal control to the surface control [33]

Vertical plumbing was accomplished using a precision zenith optical plummet. The points at the top of the shaft were defined in three dimensions by the centres of Taylor Hobson Spheres which were mounted at the pit bank, see Fig. 2

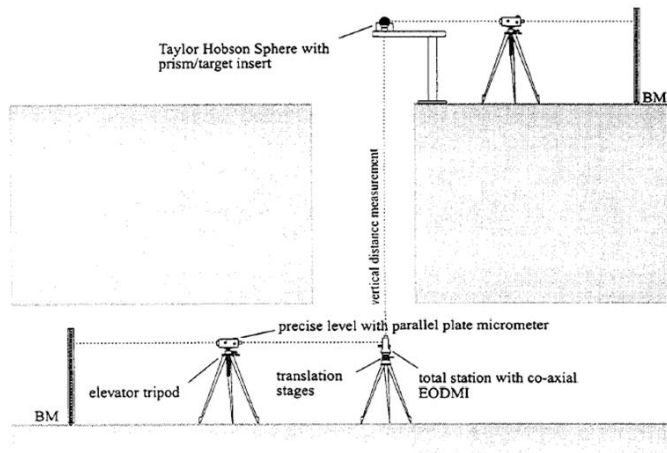


Fig. 2 Transfer of SSC's vertical control [33]

Due to the conservatism of mine surveyors and in view of scientific findings in the field, no new findings were basically achieved in the past 30 years. The method of conducting connecting surveys and orientation measurements could only

be innovated in recent years only thanks to a massive development of robotised universal surveying instruments. One of the possible methods of performing connecting surveys and orientation measurements with the use of robotised universal surveying instruments is described in the present study.

3 BASIC PRINCIPLES OF CONNECTING SURVEYS AND ORIENTATION MEASUREMENTS

This chapter describes the basic principles and methods of conducting underground connecting surveys and orientation measurements and processing their results, as they evolved over several hundreds of years in the light of the technical development in the scientific field.

The purpose of connecting surveys and orientation measurements is to project the position of the points on the basic orientation line and its direction to the mine in order to connect the underground horizontal control to the surface control.

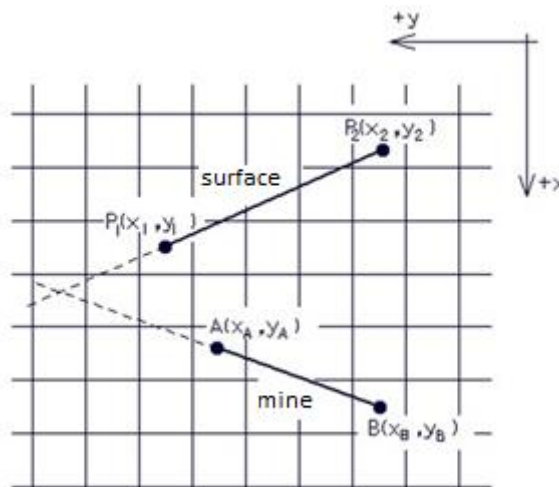


Fig. 3 Diagram of connecting surveys and orientation measurements

The basic principle of connecting surveys and orientation measurements according to [25] is to determine the position of two points A and B in a mine in a binding reference coordinate system in which at least two points on the surface, P_1 and P_2 , are known (see Fig. 3). On the basis of the coordinates of points $A[x_A, y_A]$ and $B[x_B, y_B]$, it is then possible to calculate the bearing of side AB in the same coordinate system as the one on the surface. The result of the connecting survey

and orientation measurement are the coordinates of terminal points A and B on the so called basic orientation line and of the bearing of side AB:

$$\sigma_{A,B} = \arctg \frac{y_B - y_A}{x_B - x_A} \tag{1}$$

Fig. 4 shows a diagram of the connecting survey and orientation measurement method using direction measurements, when the position of only one point, $A[x_A, y_A]$, is determined on the surface and bearing α_A is defined by means of direct magnetic or gyroscopic measurement. As a precaution against possible damage or destruction of one of the terminal points on the basic orientation line, it is advisable to determine the position of three points (so that it is possible to check the invariable position of the points by means of measuring the vertex angle in the inner point). The basic orientation line is usually selected in such a way as to prevent any disturbance of its stability as a result of extraction works, i.e., its points are located on shaft bottoms and shaft safety pillars in underground mines. In horizontal or pitch mining works, the basic orientation line is stabilised into the overlying strata of the deposit (roof of the galleries). For more details see [25].

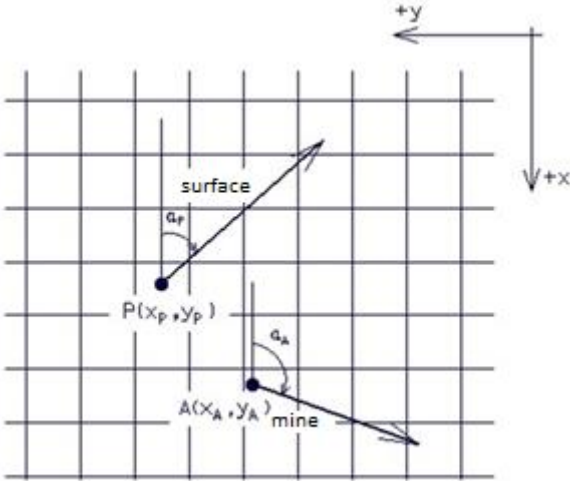


Fig. 4 Diagram of connecting surveys and orientation measurements using direction measurements

The most appropriate method is connection by means of an accurate traverse. The measurement of vertex angles in underground traverses is carried out in at least one set and the allowable deviation in the misclosure of the set depends on the required accuracy. In the case of accurate traverses, the deviation is set at $U_p = \pm 10''$ according to [36]. If the opening of a mining area consists of two shafts, one plummet is lowered in each of them. If there are more than two shafts in the mining area, the connection is performed by means of non-oriented traverses also between those shafts and all orientation results are compared on one common orientation line. The differences in the bearing values define the degree of accuracy of the measurements as well as the required control as described in [36]. If an underground mine is opened with one vertical shaft, the orientation is carried out using a gyrotheodolite or two plummets. In the case of raises, which are vertical works connecting a level with another level, and less deep shafts (100-150m) where the surrounding air is free, without water drops, it is possible to use survey patterns and steady plummets; however, this method can only be used as an orientation geodetic method. For a more detailed description of methods for performing connecting surveys and orientation measurements see, for example, [5].

Based on the description provided above it may seem that both methods are very simple; however, their practical implementation encountered and still encounters significant problems, particularly if the connected horizon is opened by one or more vertical mine outlets (shafts). The most difficult task in this respect is performing a connecting survey and orientation measurement in one vertical pit, which was not resolved with sufficient accuracy until in the second half of the last century by means of gyrotheodolites.

3.1 Historical development of connecting surveys and orientation measurements

Records of solutions to the problem of connecting the surface with an underground area date back more than 2,000 years, when no angle measuring instruments were known. A survey of a well, which was to run underground and

reach an underground adit at a predefined point, is described by Heron of Alexandria (1st century AD), see Fig. 5. A diagram of a water adit of the Fucine Lake is shown in Fig. 6.

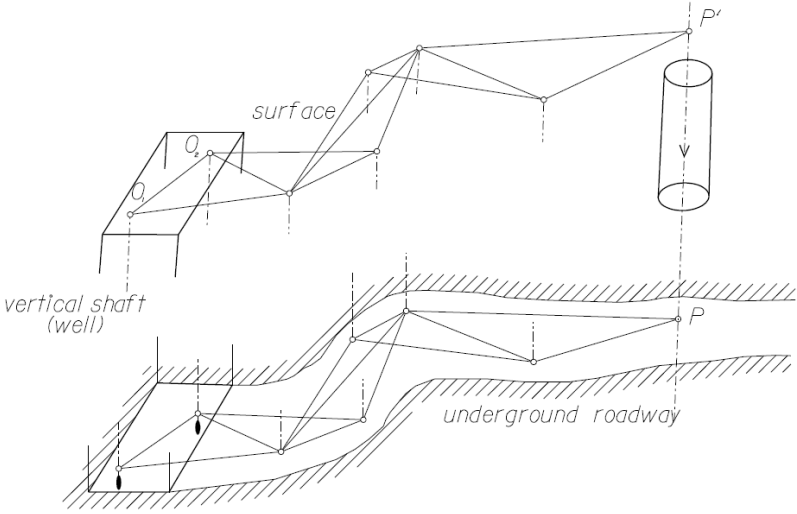


Fig. 5 Example of a connecting survey and orientation measurement according to Heron of Alexandria [25]

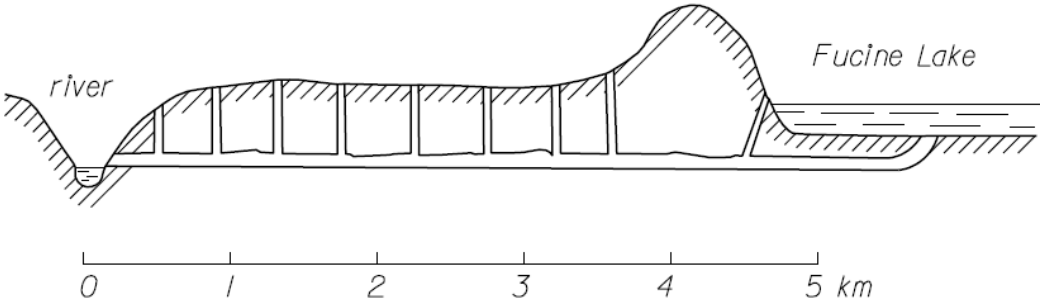


Fig. 6 Water adit of the Fucine Lake [25]

Fig. 5 shows that the task was resolved by connecting point P underground with plummets in the shaft by a triangulation network, in which all the lengths were measured. The same network was laid out from the plummets on the surface up to point P. The accuracy of the gauge points determined on the basis of the length measurement could not be high, yet satisfactory results were achieved. The Fucine adit was driven from a number of places by excavation and counter-excavation. The axis was determined by two plummets lowered in vertical shafts, which were 80 – 120 m deep.

More accurate results were achieved in connecting surveys and orientation measurements at the beginning of the 13th century, when instruments based on magnetism – compasses – started to be used for orientation measurements in Europe. An illustration and description of such a compass is given in the introduction of the aforementioned work by Georgius Agricola “De re metallica libri XII” (“Twelve Books on Mining and Metallurgy”), see Fig. 7.

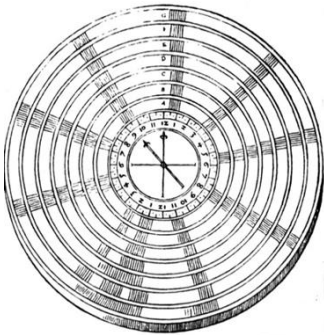


Fig. 7 *Compass according to Agricola [3]*

The needle is mounted on a steel pivot and the direction is shown on a 12-hour scale, with the hour-units being divided to four smaller ones. In his work mentioned above, Agricola also describes another method of conducting a connecting survey and orientation measurement as shown in Fig. 8



Fig. 8 *Connecting survey and orientation measurement according to Agricola [3]*

Fig. 8 illustrates that the solution consisted in a pit being excavated while a horizontal adit was driven to the pit. Measurements were performed by a plumb line and plummets determining the vertical plane on which the horizontal line directed to the shaft must also lie. Based on the similarity of the triangle, outlined under the yoke diagonal, *mensatores* (surveyors) could also calculate the necessary depth of the shaft and the length of the adit up to the cut-through point.

The compass as an instrument used for orientation measurement was replaced by theodolite as late as in the 19th century. At that time, mining operations as well as the methods of conducting connecting surveys and orientation measurements saw a rapid development. Connecting surveys and orientation measurements using two plummets lowered into one pit were performed by means of different connecting figures (triangles, quadrangles). These methods were very demanding in terms of the accuracy of the projection of the terminal points of the orientation line segment, which was often only 1.5 – 2 m long. Therefore a method of magnetic connecting surveys and orientation measurements was developed, which was less demanding in terms of the time needed and from the surveying perspective. Under this method, it is only sufficient to project to the connected horizon the position of only one point using less demanding techniques (i.e., with a lower projection accuracy). The side adjacent to the side running from the projected point was oriented using accurate magnetic theodolites (theodolites with a magnetic declinatorium).

This period is also characterised by a large number of mining companies renting mining claims in one extraction area. One of the tasks of mine surveyors, as set out in Emperor's Patent No. 146/1854 of the Imperial Code of 23 May 1854 [3], was to set out the location of mining claims underground and on the surface, as these were recorded by courts in the Mining Books. Connecting surveys and orientation measurements thus did not only involve measurement in the technical sense but also in the legal sense. This connection is still valid today, as the basic mining map resulting from measurements of the basic control points determined on

the basis of connecting surveys and orientation measurements is a technical as well as a legal document, as stated in Regulation of the Czech Mining Authority No. 435/1992 Coll., on Mine Surveying Documentation for Mining Activities and Certain Other Activities Performed by Mining Methods, as amended [36].

Thanks to the gradual development and use of steel supports and equipment and the introduction of electrical transportation in mines, it was necessary to find a new method to replace magnetic orientation. This was achieved in the middle of the last century by the introduction of gyrotheodolites in mine surveying.

3.2 Current methods of conducting connecting surveys and orientation measurements

The methods of conducting connecting surveys and orientation measurements that can be used at present, including their accuracy, are specified in Annex 1 – Position and Height Measurements within Activities Performed Underground pursuant to Section 1 of the Regulation [36], Chapter 4 – Connecting Surveys and Orientation Measurements.

3.2.1 Methods of conducting connecting surveys and orientation measurements

The method of conducting a connecting survey and orientation measurement is selected depending on the type of the opening mining (underground) work.

The horizon, the (underground) mining work, is connected and oriented by means of a traverse, which is:

- (a) conducted between the points projected by two or more shafts; or
- (b) conducted between the orientation lines stabilised on the surface near the opening of adits or pitch (underground) mining works; or
- (c) running from one orientation line stabilised on the surface near the opening of an adit or a pitch (underground) mining work and ending on at least one point projected by the shaft; or
- (d) running from the point projected by one shaft and a line oriented using a gyrotheodolite.

If the conditions described under (a), (b) and (c) cannot be met, the horizon, the (underground) mining work will be oriented using an appropriate geodetic orientation method (e.g., by means of two plummets) or by a gyrotheodolite and at least one plummet before the length of the (underground) mining work under excavation reaches 300 metres.

The necessary measurements must be performed and traverses must be evaluated no later than 30 days after the horizon can first be connected and oriented using any of the methods under (a), (b), (c) and (d) above.

The method of connecting and orienting the horizon by means of one shaft and two plummets can only be used in exceptional cases when a more accurate method cannot be used.

3.2.2 Accuracy of connecting surveys and orientation measurements

The accuracy of connecting surveys and orientation measurements depends on the accuracy in the position of the basic orientation line, or rather on the values of mean errors in the position of the points on the basic orientation line: m_{xA} , m_{yA} , m_{xB} , m_{yB} and their bearing $m_{\sigma AB}$. The required accuracy is defined by the accuracy of the determined position of the points of the mining works on the border of the extraction area. It depends on the mean error resulting from an incorrect orientation of the basic orientation line and from errors generated during the measurement of the non-oriented traverse, which can most easily be characterised by the transverse deviation.

Assuming that the traverse is adjusted, transverse deviation Q_{σ} caused by error $m_{\sigma AB}$ in orientation line segment AB is defined by the following relation:

$$Q_{\sigma} = m_{\sigma AB} L \quad (2)$$

Due to errors occurring in the measurement of vertex angles m_{ω} in the traverse, transverse deviation Q_t occurs, which is defined by the following relation:

$$Q_t = m_{\omega} L \sqrt{\frac{L}{3s}} \quad (3)$$

In the abovementioned relations (2) and (3):

L ... is the total length of the traverse; and

s ... is the mean length of the traverse sides.

The total error, or uncertainty of the position of point K, is defined by the sum of both transverse deviations

$$Q_c = Q_\sigma + Q_t \quad (4)$$

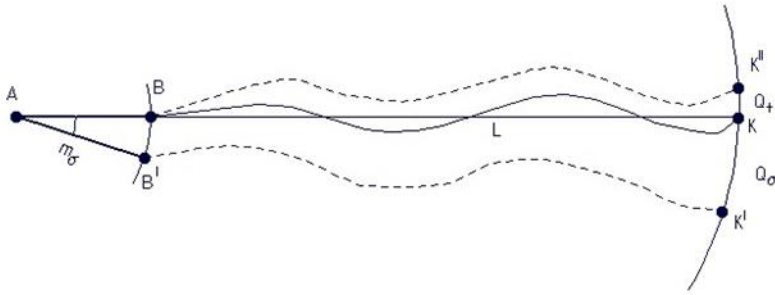


Fig. 9 Derivation of the accuracy of the connecting survey and orientation measurement [24]

The optimum accuracy of the bearing of the basic orientation line in a connecting survey and orientation measurement can be determined on the basis of the condition requiring that the transverse deviation caused by incorrect orientation Q_σ must not be higher than the transverse deviation of the traverse on the border of extraction area Q_t , i.e.

$$m_{\sigma AB} L = m_\omega L \sqrt{\frac{L}{3s}} \quad (5)$$

$$m_{\sigma AB} = m_\omega \sqrt{\frac{L}{3s}} \quad (6)$$

The *a posteriori*, i.e. real accuracy of the measurement can be calculated on the basis of deviations in the direction of basic orientation line Q_σ and of the

position deviations of terminal points O_x , O_y , or alternatively O_P . The accuracy in determining the bearing of the basic orientation line is laid down by the Regulation [36] and is also defined from the theoretical perspective in [22].

Depending on the required results and accuracy of measurements, the Regulation [36] distinguishes among measurements which are:

- (a) very accurate;
- (b) accurate;
- (c) technical;
- (d) special.

Special measurements mean special instances when it is necessary to observe the accuracy determined by the project (e.g., tunnelling of the underground).

Connecting surveys and orientation measurements must meet the criteria set for very accurate measurements, as referred to under (a) above.

As mentioned earlier, the purpose of connecting surveys and orientation measurements is to determine the position of the basic horizontal control, defined by the basic orientation line underground, which in turn is determined by exhaustively defined traverses. Therefore, the determination of the position of the basic orientation line is affected by the accuracy of the measurement of angles (directions) and lengths, by the accuracy in the determination of the position of a projected point and the accuracy in the determination of bearings using a gyrotheodolite.

3.2.3 Accuracy of angle measurements in connecting surveys and orientation measurements

In the category of very accurate measurements, the vertex angle of a traverse must be determined in at least one set. The allowable deviation in the misclosure of the set is

$$U_{VP} = \pm 5'' . \quad (7)$$

Vertex angles in underground traverses are determined on the basis of uninterrupted measurements. If the measurements are interrupted, it is only possible to resume them provided that the difference between the original and the newly surveyed last vertex angle does not exceed

$$d_{VP} = \pm 15'' \quad (8)$$

(this applies to very accurate measurements).

3.2.4 Accuracy of length measurements in connecting surveys and orientation measurements

Lengths in underground traverses can be determined by means of direct measurement, compared surveying tapes or indirect measurement, by telemeters.

For very accurate measurement, lengths are measured:

- a) *by a tape* three times in different positions of the tape;
- b) *by a telemeter* (there and back).

When using a tape, the values so measured can be used provided that the difference between them does not exceed

$$d_{VP} = \pm 0.4 \cdot 10^{-3} s \text{ [m] } , \quad (9)$$

in the case of very accurate measurements, where s is the length measured in metres.

In very accurate and accurate measurements, lengths measured by the tape before their reduction for the horizontal position will be corrected to reflect systematic errors resulting from incorrect division of the tape, from differences in the temperature upon surveying tape standardisation and during measurements, from the extension of the surveying tape by the tensioning force, from the deflection of the surveying tape, and from different altitude and cartographic distortion.

When using a telemeter, the mean relative error of the length measured must not exceed the value of 1 : 18 000 in the case of very accurate measurement. Lengths are corrected to reflect errors resulting from atmospheric conditions, altitude and cartographic distortion.

3.2.5 Accuracy in determining the position of a projected point in connecting surveys and orientation measurements

In order to survey and calculate traverses mentioned in Chapter 4.2.1 under (a), (c) and (d), the zero and terminal points need to be projected from the surface to the underground. The projection of a point position underground will be described in more detail in a separate chapter of this study, as correct projection of a point position is paramount to the accuracy of connecting surveys and orientation measurements, given the accuracy that can now be achieved in determining lengths, angles and directions.

The allowable deviation in the position of the projected point pursuant to the Regulation [36] is:

$$\pm 7 \cdot 10^{-3} \text{ m.} \quad (10)$$

This value applies to any method and depth of point projection.

3.2.6 Accuracy in determining the point bearing in connecting surveys and orientation measurements using a gyrotheodolite

The specific accuracy of connecting surveys and orientation measurements of the traverse running from a point projected by one shaft and a line oriented by the gyrotheodolite is laid down by the Regulation [36]. The accuracy in orienting the basic orientation line measured independently at least twice from two different positions of the gyrotheodolite is defined by the maximum mean error of:

$$m_{GI} = \pm 10'', \quad (11)$$

in the case of very accurate measurements.

3.2.7 Connecting surveys and orientation measurements by means of a traverse running between the points projected by two or more shafts

This method of conducting connecting surveys and orientation measurements can be used in cases where the (underground) deposit opening work consists of two or more vertical shafts. The shafts must be excavated to the level of the horizon on which the position of the basic orientation line is to be determined. This is a very accurate and, from the surveying perspective, simple method of orientation of the basic underground horizontal control, which is based on the measurement of a non-oriented traverse between two defined points.

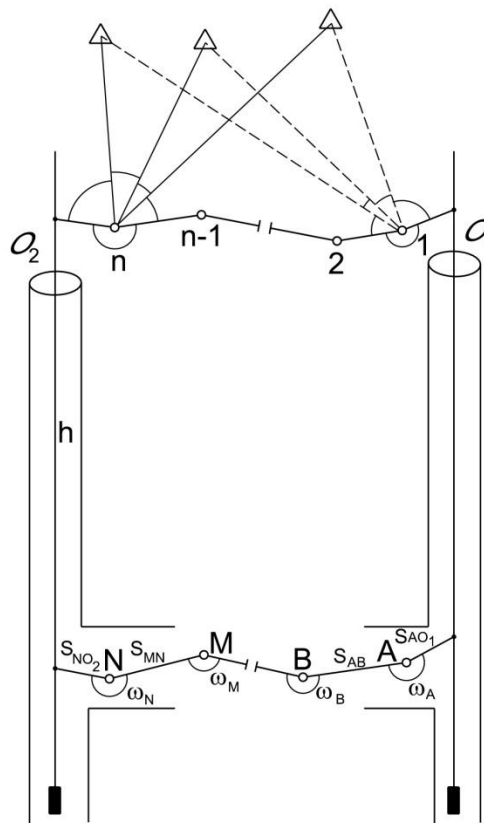


Fig. 10 Connecting surveys and orientation measurements by means of two vertical shafts

As shown on Fig. 10, one point from each of the two shafts is projected to the connected horizon, e.g., using mechanical plummets O_1 , O_2 . The coordinates of the

position of the plummets on the surface are determined based on the traverse points at the individual pit banks pursuant to the rules laid down in Annex 2 – Position and Height Measurements within Activities Performed on the Surface pursuant to Section 1 of the Regulation [36], Chapter 3. *Accuracy in determining the underground horizontal control.*

In a mine, this method of conducting connecting surveys and orientation measurements will be implemented by surveying the traverse with vertices A to N (Fig.10), to which we will connect the position of plummets O_1 and O_2 by surveying the respective connecting angles and lengths. The traverse must meet the accuracy criteria specified in Annex 1 – Position and Height Measurements within Activities Performed Underground pursuant to Section 1 of the Regulation [36], Section 4.2.1 *Connecting surveys and orientation measurements by means of two shafts.*

3.2.8 Connecting surveys and orientation measurements by means of a traverse running between orientation lines stabilised on the surface near the opening of an adit or pitch mining work

Where the (underground) deposit opening work has the form of a horizontal or pitch mining work (e.g., adit, inclined drift or an inclined pit), connecting surveys and orientation measurements are performed by means of a traverse oriented on both ends and connected in accordance with the principles and accuracy criteria laid down in Annex 1 – Position and Height Measurements within Activities Performed Underground pursuant to Section 1 of the Regulation [36], Chapter 2. *Measurement accuracy.* A diagram depicting this method of conducting connecting surveys and orientation measurements is shown in Fig.11.

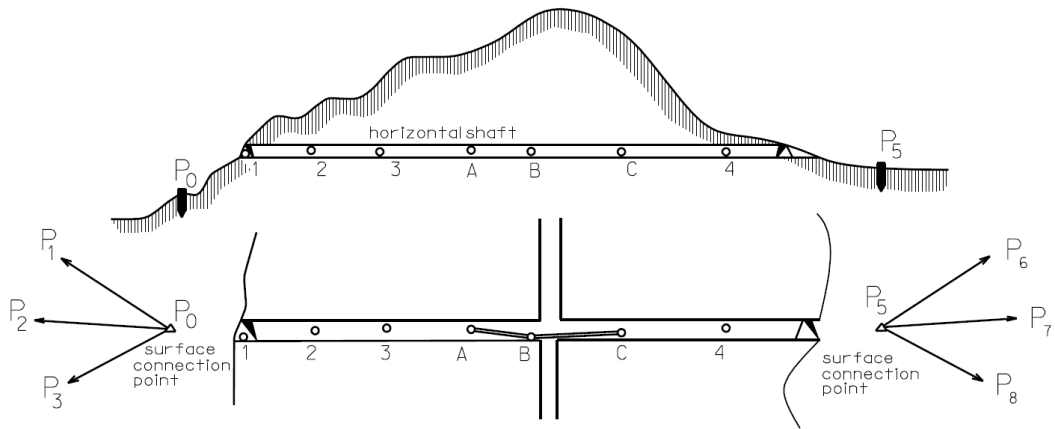


Fig. 11 Connecting surveys and orientation measurements by means of a traverse running between orientation lines stabilised on the surface near the opening of an adit or pitch mining work

Basic underground horizontal control points ($P_0 - P_8$), determined by means of the very accurate traverse established on the basis of basic horizontal control points, are permanently stabilised before the openings of the adit. The basic underground horizontal control points are then used to determine the coordinates of the points (A, B, C) on the basic orientation line, which is stabilised at places where rock pressure is not likely to manifest.

3.2.9 Connecting surveys and orientation measurements by means of a traverse running from one orientation line stabilised on the surface near the opening of an adit or pitch mining work and ending on at least one point projected by the shaft

This method of conducting connecting surveys and orientation measurements can be applied in cases where the (underground) deposit opening work has the form of a horizontal or pitch mining work (e.g., adit, inclined drift or an inclined pit) and at least one vertical shaft. A diagram depicting this method of performing connecting surveys and orientation measurements is shown in Fig. 12.

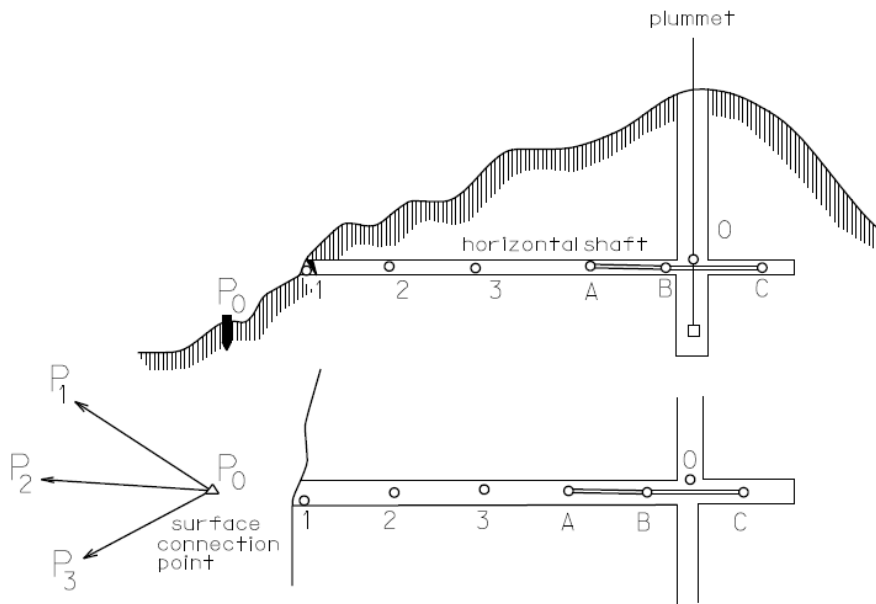


Fig. 12 *Connecting surveys and orientation measurements by means of a traverse running from one orientation line stabilised on the surface near the opening of an adit or pitch mining work and ending on at least one point projected by the shaft*

Connecting surveys and orientation measurements of this type are performed by means of a traverse oriented on one end and connected on both ends in accordance with the principles and accuracy criteria laid down in Annex 1 – Position and Height Measurements within Activities Performed Underground pursuant to Section 1 of the Regulation [36], Chapter 2. Measurement accuracy.

Basic underground horizontal control points ($P_0 - P_3$), determined by means of the very accurate traverse established on the basis of basic horizontal control points, are permanently stabilised before the opening of the adit. The basic underground horizontal control points define the traverse ending on the point which is projected from the surface to the connected horizon via a vertical shaft. The traverse is then used to determine the coordinates of the points (A, B, C) on the basic orientation line, which is stabilised at places where rock pressure is not likely to manifest.

3.2.10 Connecting surveys and orientation measurements by means of a traverse running from the point projected by one shaft and a line oriented using a gyrotheodolite

This method of conducting connecting surveys and orientation measurements can be used in cases where the (underground) deposit opening work has the form of only one shaft. It also represents the fundamental technique of performing connecting surveys and orientation measurements. Czechoslovakia was one of the first countries in the world to acknowledge this method, incorporating it in the Mine Surveying Regulation [39] as early as in 1962.

A diagram depicting the connection by means of a point and direction is shown on Fig. 13. This is the simplest method of connecting and orienting the horizon. Basic underground horizontal control points are stabilised on the surface, which are then used to determine the coordinates of the position of the projected point (e.g., projected by means of a plummet) by establishing connecting angle ω_A and length s_{AO} . Points C and D on the basic orientation line are stabilised on the connected horizon at the shaft bottom, whose position will be calculated on the basis of connecting angle ω_C , lengths s_{OC} , s_{CD} and side bearing σ_{CD} determined by the gyrotheodolite.

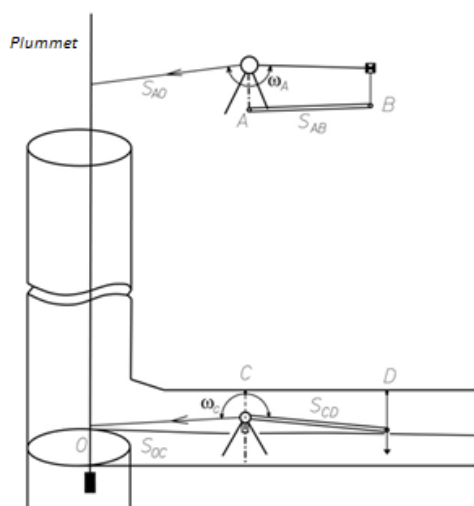


Fig. 13 Connecting surveys and orientation measurements by means of a point and direction determined by the gyrotheodolite

4 POINT PROJECTION TO THE UNDERGROUND

If the opening mining work has the form of a shaft (see Chapters 3.2.7 3.2.9, and 3.2.10), an indispensable part of a connecting survey and orientation measurement is the point projection from the surface to the connected horizon. Point projection can be performed in two different ways:

- By optical projection;
- By mechanical projection.

4.1 Optical point projection to the underground

The optical projection can be carried out by means of a vertical sight line set out by a telescope or laser. The use of this method of point projection to the underground is limited by the depth of the connected horizon, the shaft environment (dust, humidity and irregular arrangement of layers of air of different density and temperature) as well as by hydrological aspects. The disadvantage of laser projection instruments is the dispersion of the laser beam, which creates a mark having a diameter of approx. 10^{-2} to 10^{-3} in larger depths, which is not of the same intensity and clear delimitation [13]. Therefore, the method of optical point projection to the underground can only be used in shallow pits or foundations pits for utility tunnels with a maximum depth of 50 to 100 m, provided that the criteria for point projection pursuant to [36] are met.

4.2 Mechanical point projection to the underground

The mechanical point projection to the connected horizon is still performed by means of specially adjusted plummets. Fig. 14 depicts such plummet: 1 – suspension frame, 2 – lead plates, 3 – plummet weight coating.

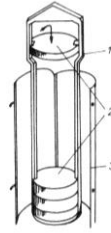


Fig. 14 Plummet for complex projection [24]

The plummet is comprised of a weight, weighing from several tens to several hundreds of kilograms, which is suspended on a wire of high strength and appropriate cross-section reeled on winch with a brake. The position of the plummet in the plumb line is determined by calculation as the centre of the swing of the plummet in two mutually perpendicular directions. See 15: 1 – mirror of the plummet, 2 – projecting rays.

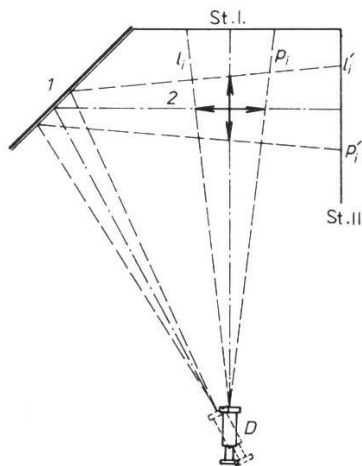


Fig. 15 Observation of plummet swings [25]

The swing centre is determined from one theodolite station as follows: a projection apparatus (see Fig. 16) is fastened behind the plummet so that one (front) scale is perpendicular to the theodolite sight line and the other one is parallel to it. The theodolite is placed 5 to 8 metres from the plummet to easily allow making estimates of the fraction of the smallest division on the scale (usually 1mm). The axis of pitch of the telescope must be at the same height as the scale of the projection apparatus, otherwise it would be impossible to read the inflection

point in the mirror. These facts exclude the possibility of swings being observed from a point on the basic orientation line, from which the connecting angle and the distance to the plummet are determined.

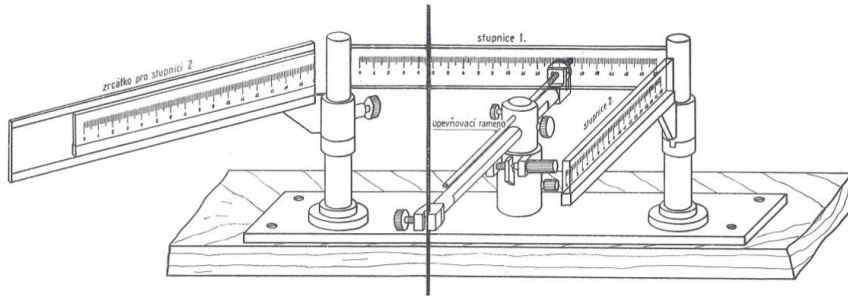


Fig. 16 *VŠB projection apparatus [25]*

The observation of the swing centre is initially performed on the first scale by the deflection of the plummet from the position of equilibrium and its free motion in the direction parallel to the first scale. Using the theodolite telescope, the plummet motion is observed and extreme positions of its swing are read from the scale. A total of 10 full swings, i.e., 11 inflection points on the left side of the plummet swing and 10 inflection points on the right side of the plummet swing (see Fig. 17), are so determined.

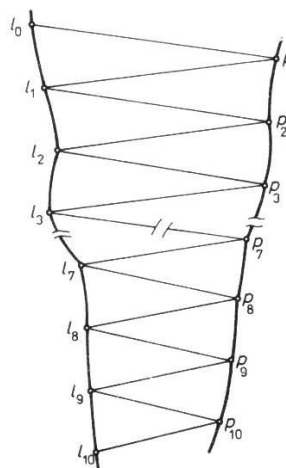


Fig. 17 *Diagram of plummet swings [25]*

On the basis of all readings of left and right inflection points, arithmetic means are calculated and the value of the swing centre is then calculated from both values of the arithmetic means. Two additional swing sets of swings are determined in the same way. Hence, a total of three swing centre values based on three sets of swings are determined, the final swing centre value being their arithmetic mean.

The method described above is applied to determine the centre of the plummet swings in the direction perpendicular to the direction of the first set of swings.

During point projection to great depths (currently 800 to 1.000 metres) it is advisable, for the sake of accurate determination of the plummet position in the plumb line, to apply the method while using several different weights. The weights must be adjusted so as to allow setting several weighting possibilities. To guarantee a constant wind force affecting the plummet on variable volume of weights, the weights have to be provided with sheet-metal coating with constant surface.

This projection method, invented and developed by prof. Wilski, is based on the assumption that, in airflow, the plummet does not swing around the correct projection of the suspension point, as the airflow force exerts constant effect on the plummet. The airflow, causing the plummet to deflect, makes the plummet swing regularly to the right and to the left, but not around the correct projection of the suspension point. The shift of the swing centre increases with the kinetic energy of the airflow, which depends on the amount of winds flowing through the shaft and on their speed. To ascertain the deflection, it is necessary to use at least two different weights. The accurate position of the plummet in the plumb line can then be established by just two observations of swings with two different weights. If several weights are used, the accurate position of the plummet can be determined based on a redundant number of observations by means of an adjustment by least squares (using the mean squared error method). Wilski's complex projection is described in more detail for example in [25].

After the accurate position of the plummet in the plumb line is calculated, this position is secured by means of an arresting mechanism of the projection apparatus. With the plummet stabilised in the plumb line, it is possible to measure the directions and lengths from the points on the basic orientation line. The angles are measured in at least two sets and the lengths are measured in accordance with the principles applicable to very accurate measurement of lengths [36]. The very abbreviated description of the plummet projection provided above clearly indicates that the entire connecting survey and orientation measurement is a very demanding process not only from the perspective of the measurement and calculation accuracy but also with respect to ensuring safety at work since a substantial part of the works is carried out directly in the shaft. Following the consultation with the safety officer, the persons supervising those works must propose a work procedure and the relevant safety measures, which are then approved by the mine manager.

Depending on the nature of the works, particularly the following precautions must be proposed in the aforementioned measures:

- a. A solid scaffold (A) on the pit bank level on the surface and on the surveyed level (B) has to be set up to protect the mine surveyor and his assistants from falling into the shaft during the survey.
- b. An extra solid scaffold (C) has to be set up under the level in the area where the weight of the plummet is manipulated.
- c. A protection scaffold (D) above the surveyed level has to be set up to protect the surveyor and the projection apparatus against falling fragments of the shaft brickwork and other objects.

The technical solution of the connecting survey is shown in Fig. 18.

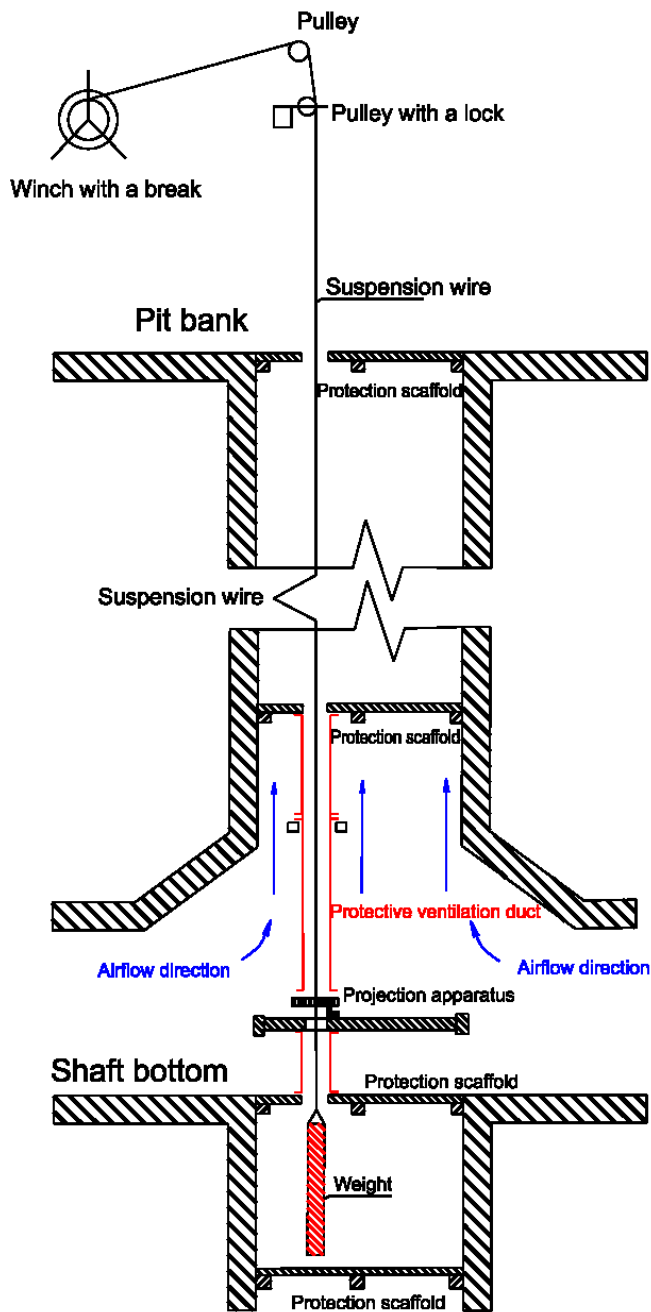


Fig. 18 *Technical solution of the connecting survey*

4.3 Effect of airflow pressure on the determination of the accurate position of the plummet in the plumb line

The technique of complex projection of plummets invented by prof. Wilski was based on the assumption of steady and constant airflow effect and spiral movement of air in the shaft.

However, the assumption of steady and constant airflow effect is hard to meet in practice. It can only be achieved by switching off the main fan in a non-gaseous mine. A partial solution to the problem, which is used frequently, consists in reducing the revolutions of the main fan in gaseous mines on days of work interruption. Despite problems with maintaining constant airflow and holes in the hypothesis of spiral airflow in shafts, which were proven, for example, in Oglobin's works, Wilski's complex projection offered an important solution to the problem of conducting connecting surveys in separate shafts.

As follows from the above, Wilski avoided calculations of the amount of the airflow pressure and the effect of the airflow on the plummet by assuming it is constant. To calculate the deflection of the plummet from the plumb line, he used several weights.

Calculations of the actual amount of pressure and the airflow effect were dealt with, for example, by Drumm in his studies [7].

The most characteristic feature of the airflow in a shaft is its speed. The maximum allowable speed in a shaft is defined in Section 85 (*Mine Air Speed*) of the Regulation [37]. The maximum speed is $10 \text{ m}\cdot\text{s}^{-1}$ in a mining work with regular transport of people.

The way in which the airflow moves through the shaft depends on its speed and on the size of the cross-section of the shaft with equipment.

At very slow speeds, the airflow runs through the shaft straight and its speed increases from the shaft lining to the centre of the shaft, where the airflow reaches

its maximum speed. Hence, the airflow has the form of cylinder layers with different speeds, ranging from $v = 0$ to $v = max$. (laminar movement).

At higher speeds, the movement is more complex and irregular, similar to spiral movement; however, its speed near the shaft lining is slow.

The dependencies between the airflow and an object located in it are described in [34].

The calculation of the airflow pressure on the plummet and the subsequent calculation of the deflection of the plummet from the plumb line, which was made by prof. Neset in [25] and was based on [34] and in Fig. 19, cannot be used for accurate determination and elimination of deviation W_0 for other reasons affecting the irregularities in the projection of the point position to the underground by the plummet (secondary and longitudinal oscillations, etc.). However, it can be a tool for a mine surveyor, helping him to choose the most appropriate measurement method and technique to achieve the best results.

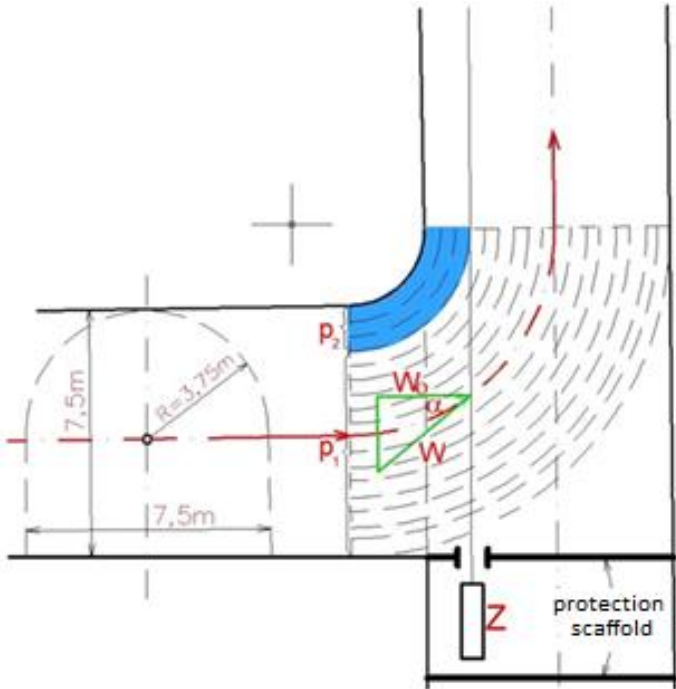


Fig. 19 Ideal airflow passage from the shaft bottom to the upcast shaft [34], [24]

The biggest effect of the airflow is to be expected at the place where it passes from the shaft bottom to the upcast shaft or where it leaves the downcast shaft and reaches the shaft bottom. This is where nearly the entire deflection of the wire from the plumb line (approx. 9/10) originates. In Fig. 19, p_1 indicates the part of the airflow having effect on the plummet, while p_2 shows the part having no effect. An important prerequisite for ensuring minimum airflow effect on the plummet weight (Z) is its location in the space below the protection scaffold. To mitigate the airflow effect on the plummet wire, the wire needs to be protected in the area of the shaft bottom by a protective ventilation duct (see Fig. 18).

5 INNOVATED METHOD OF CONDUCTING CONNECTING SURVEYS AND ORIENTATION MEASUREMENTS

With the progressive extraction of coal seams in increasingly greater depths and with the effort to exploit efficiently the coal reserves between individual big mines in the Karviná part of the Ostrava-Karviná Coal District (OKR), it is necessary to interconnect the mining compounds (mines) with opening works for economic, transport, extraction and ventilation purposes. Although all horizontal controls of the mines in the OKR mines are recorded in the Datum of Uniform Trigonometric Cadastral Network, it is necessary, for the interconnection of mine fields itself, to carry out new connecting surveys and orientation measurements. Given the depth of connected horizons of the mining works, climate conditions in the shafts and the required accuracy of the projected point position, the Institute of Geodesy and Mine Surveying at the Faculty of Mining and Geology of the VŠB – Technical University in Ostrava has developed a new plummet swing observation method.

The Regulation [36] imposes the obligation to survey all mining works in the national reference system of the Datum of Uniform Trigonometric Cadastral Network. The aim of connecting surveys and orientation measurements performed on the surface is to determine the position of the terminal points of the projected line segment and, in particular, their bearing. The connection of the horizon in a mine has the objective of transferring the coordinate values from the projected line segment to the points constituting the basic orientation line of the connected mining work. Connecting surveys and orientation measurements conducted via one or more shafts are performed by means of a plummet (or plummets) lowered into the shafts. In order to determine the coordinates of the plummets at the pit bank, it is necessary to set up an artificial scaffold in the shaft cross-section for the purposes of health and safety of the workers carrying out the length measurement.

The length measurement is performed by means of a calibrated measuring tape. The inconvenience of this traditional solution is that the work consumes a considerable amount of time and the organisation of work is difficult as safety has to be ensured also on the connected horizon. The financial costs of the whole project are not negligible either. Furthermore, direct length measurement by means of a tape is subject to various systematic errors and the measured length has to be corrected accordingly.

In the proposed solution, the connecting survey and orientation measurement is carried out by means of a universal measuring instrument with a prism coaxially inserted in the suspension above the plummet, which determines the coordinates of the terminal points of the projected line segment on the surface as well as in the mine. The lengths are not measured using a tape but by means of an optical telemeter.

For the swing observation, the new method uses a robotised universal measuring instrument and a suspension for coaxial insertion of the omnidirectional prism above the plummet. The plummet swings around its plumb line and its individual positions are continuously calculated from the data measured in the local coordinate system which is referenced to the points on the basic orientation line on the connected horizon. To define the coordinates of the basic orientation line points, the bearing is determined using a gyrotheodolite. The method of conducting connecting surveys and orientation measurements described above allows faster progress of surveying works, increases health and safety in mines and facilitates the calculation process to determine the position of the plummet in the plumb line.

5.1 Indirect measurement of lengths in connecting surveys and orientation measurements

The traditional length measurement is performed by means of a calibrated measuring tape. For the sake of health and safety of the workers carrying out the length measurement, it is necessary to set up an artificial scaffold in the shaft cross-

section in order to determine the coordinates of the plummet at the pit bank. The inconveniences of the traditional length measurement by tape used in connecting surveys and orientation measurements are eliminated by the proposed solution, which uses a hinge allowing a prism to be coaxially inserted in the suspension above the plummet (see Fig. 20):



Fig. 20 Suspension for coaxial insertion of a prism

Legend for Fig. 20, 1 – Screw for central fastening of a steel wire, 2 – Casing with bearings allowing the orientation of the suspension, 3 – Supporting plates, 4 – Pivot for the attachment of the surveying prism, 5 – Omnidirectional surveying prism, 6 – Connecting bars.

The connecting survey and orientation measurement is then carried out by lowering one or two plummet on a steel wire in the shaft (depending on the surveying method selected), with an omnidirectional prism being coaxially attached to the suspensions. The coordinates of the projected plummet position at the pit

bank are established by the direction and length measurement from known points whose position is defined in the national reference system of the Datum of Uniform Trigonometric Cadastral Network, as laid down in Decision of the Government of the Czech Republic No. 430/2006 Coll., hereinafter referred to as [38]. Length measurements, which are essential for the determination of the coordinates, are implemented by means of an electro-optical telemeter focused at the omnidirectional surveying prism in the position on the surface. To determine the plummet coordinates at the pit bank, the suspension for the omnidirectional prism is lowered to the connected horizon.

After the stabilisation of the plummets in the plumb lines, the connecting survey and orientation measurement is repeated on the connected horizon, with the directions and lengths being measured both on the omnidirectional prisms as well as on the basic orientation line points (whose coordinates may be subsequently determined on the basis of the quantities so read). Examples of use of the device in different types of connecting surveys and orientation measurements are illustrated on the figures below:

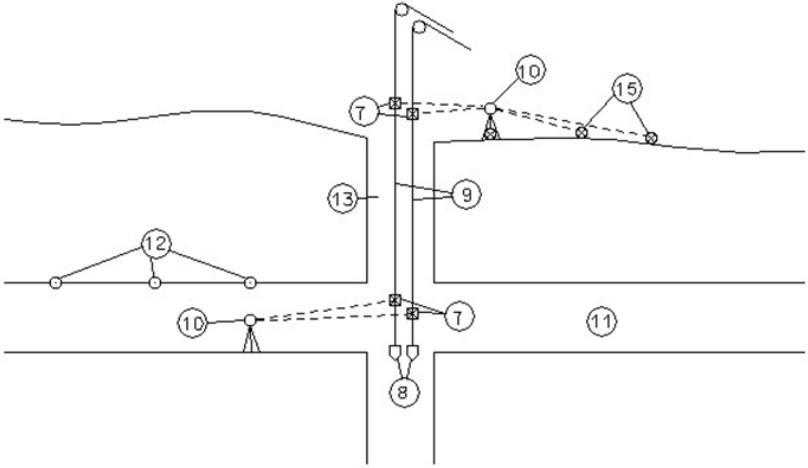


Fig. 21 *Connecting survey and orientation measurement by means of one shaft and two plummets*

Legend for the figures:

7. Suspension for coaxial insertion of a prism
8. Plummet
9. Steel wire
10. Electro-optical telemeter
11. Connected horizon
12. Basic orientation line
13. Shaft
14. Gyrotheodolite
15. Known (defined) points

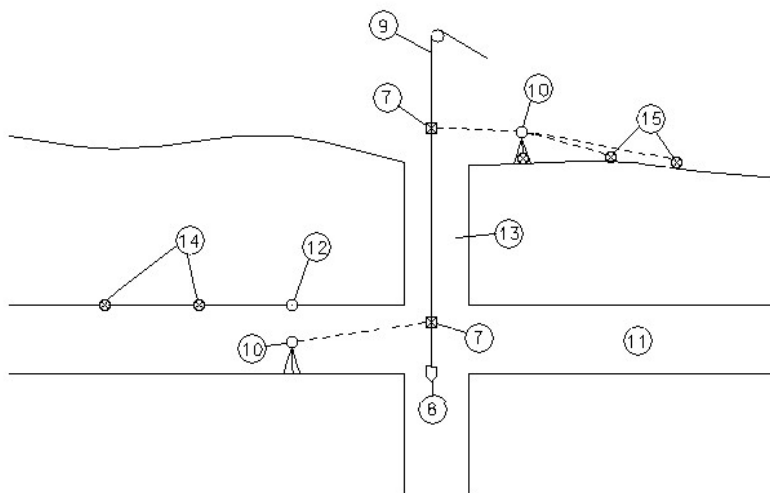


Fig. 22 *Connecting survey and orientation measurement based on a point projected by one shaft and a line oriented by the gyrotheodolite*

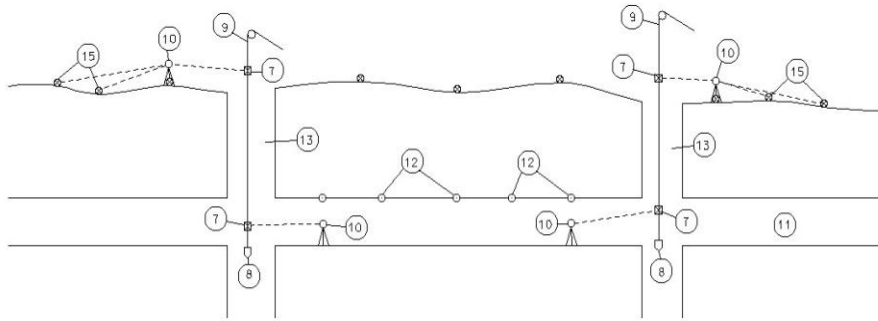


Fig. 23 *Connecting survey and orientation measurement by means of a traverse running between the points projected by two shafts*

5.2 Indirect length measurement applied in driving a utility tunnel in the centre of Ostrava

The technique of indirect length measurement by means of an electro-optical telemeter in connecting surveys and orientation measurements was verified in driving a utility tunnel in the centre of the city of Ostrava. The opening work of the utility tunnel consisted of three rectangular shafts driven up to 10m below the surface and having the following dimensions: shaft D – 6.20 x 7.20 m, shaft E – 6.70 x 4.90 m and shaft F – 4.60 x 4.80 m. The utility tunnel was driven by four simultaneously running headings, using the heading – counter-heading system (see Fig. 24, where: D, E, F – foundation pits, V1, V2, V3 – technological boreholes, K7 – K20 – utility tunnel chambers), in the following directions: shaft F – chamber K17, shaft E – chamber K14, shaft E – chamber K12, shaft D – chamber K7. The lengths of the excavated sections were as follows: D – E section – 438 m and E – F section – 276 m. During the tunnel drivage, the connecting surveys and orientation measurements were performed in four stages. All surveys were conducted using accurate measurement methods. This accuracy was determined pursuant to [36].

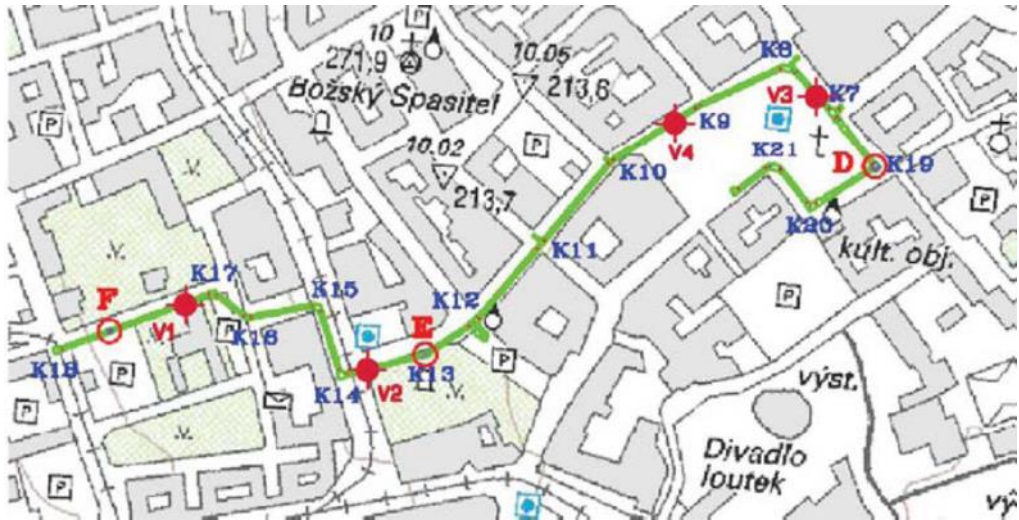


Fig. 24 The utility tunnel route with chambers, foundation pits and technological boreholes [29]

5.2.1 Stage I

Given the opening work of the utility tunnel mentioned above (three shafts), it was necessary to apply the method of two plummets being projected through a single shaft and the connecting pattern being represented by a line segment. The driving direction was determined based on the control network points. Holes for plummet suspension were bored into the brackets welded at all the pit banks. The coordinates of the projected line segment (plummets) were determined in the national reference system of the Datum of Uniform Trigonometric Cadastral Network from the surveying point situated near the shaft, by means of an omnidirectional prism coaxially inserted into suspension above the plummet. The plummets in the shaft determined the direction for driving the utility tunnel until the driving direction could be determined directly by the points located in the utility tunnel tube itself.

5.2.2 Stage II

After approx. 6 metres of the utility tunnel had been driven, the plummets were again fixed at the pit bank. In view of the shallow depth of the underground work, a WILD ZNL optical plummet was used to project the line segment to the horizon. The universal measuring instrument was centred under the hole of one of

the brackets at the pit bank, while the plummet was lowered through the hole of the other shaft. The driving direction was reported to the utility tunnel tube and stabilised by a set of four points at its axis.

5.2.3 Stage III

When 30 – 40 m of the excavation were completed at the headings, it was necessary to refine the utility tunnel connection because the lengths of the line segments projected in the shafts (F – 4.113 m, E – 5.814 m, D – 6.214 m) did not guarantee a successful breakthrough. Connecting surveys and orientation measurements were refined after technological boreholes 1, 2, and 3 had been drilled in the manner described below. The diameter of the boreholes so drilled was 300mm and the boreholes were then cased off. The connection on the surface was achieved by reconnecting one plummet at the pit bank. The second point was marked by a prism installed above the borehole mouth. The first point on the line segment was projected on the horizon by the optical plummet, the other one by means of the traditional mechanical projection using a coaxially inserted omnidirectional prism at the borehole axis. This line segment was used at each shaft for surveying three pre-set points situated in the utility tunnel vault (basic orientation line), see Fig. 25 and Fig. 26. The measurements performed in the manner described above helped increase the lengths of the connecting line segments (shaft – borehole) reported to the utility tunnel horizon.

Legend for Fig. 25 and Fig. 26: A – suspension with a plummet and omnidirectional prism, B – surveying prism, C – bracket for attaching plummets at the pit bank, D – universal measuring instrument (Leica TC 1700), E – orientation to the control network points, F – foundation pit, G – technological borehole, H – utility tunnel, 1,2,3 – points for surveying the basic orientation line.

underground, are determined from the surveying perspective by means of an electro-optical telemeter and an omnidirectional prism coaxially inserted in the suspension above the plummet. The use of the electro-optical telemeter mitigates the effect of systematic errors in direct length measurement by means of a calibrated measuring tape, and physical and geometrical reductions may be entered directly into the software of the telemeter. The resulting lengths are then corrected to reflect the influence of such errors.

The method of indirect length measurement using an electro-optical telemeter in connecting surveys and orientation measurements was verified in practice when a utility tunnel was driven in the centre of the city of Ostrava. Based on such practical verification, the instrument intended for indirect length measurement in connecting surveys and orientation measurements was registered by the Industrial Property Office of the Czech Republic as utility design no. CZ 21047 U1. An application for the registration of the technique of indirect length measurement in connecting surveys and orientation measurements as a patent – invention was submitted to the Industrial Property Office of the Czech Republic under no. PV 2010-165.

The instrument can be used for performing connecting surveys and orientation measurements in mine surveying, underground engineering, activities carried out using mining methods pursuant to [25], and speleology. The design of the instrument, with bearings fixed in the suspension casing, enables the insertion of a standard unidirectional surveying prism (the suspension can rotate in all directions). The advantages of using this instrument for length measurement in connecting surveys and orientation measurements include health and safety and organisation of work, time efficiency, length measurement accuracy, possibility of entering corrections to reflect systematic errors directly in the instrument software, process efficiency and flexible use of the solution.

More details about the method used for driving a utility tunnel in the centre of Ostrava can be found in [29] and in [1].

5.3 Basic principles of the new method of swing observation for the purposes of determining the accurate position of the plummet in the plumb line in connecting surveys and orientation measurements

The inconveniences of the traditional observation of plummet swings and length measurement in connecting surveys and orientation measurements in shafts are eliminated by the suggested solution, which consists of using a suspended omnidirectional prism inserted into the plummet weight and which was developed at the Institute of Geodesy and Mine Surveying, Faculty of Mining and Geology, VŠB – Technical University of Ostrava.

The device is comprised of a suspension for the coaxial insertion of the omnidirectional prism (see Fig. 27), which is composed of screws for central fastening of the wire (1), a casing with bearings allowing the orientation of the suspension (2), supporting plates (3), a pivot for the attachment of the surveying prism (4), an omnidirectional prism (5), bars connecting the top and the bottom supporting plate of the suspension (6) and an adjusted plummet with a sheet-metal coating (7). The suspension is equipped with the coating in order to guarantee constant wind force exerted on the plummet in the case of use of different weights.



Fig. 27 *Suspension for an omnidirectional prism coaxially inserted above the plummet*

During the projection of the point from the surface to the connected horizon, it is necessary to first fix a pulley and a wire lock at the pit bank. The weighted wire is slowly lowered into the shaft so that it does not swing and get caught on the shaft equipment. A better and practice-tested way is to lower slowly the wire lead by a surveyor from the mine cage. However, this method requires the observation of all safety rules and measures approved by the mine manager.

After the wire is lowered to the connected horizon, the suspension is attached to the wire and individual weights are added one by one until the required weight is reached. While weights are being added, it is necessary to anticipate a considerable elastic extension of the wire, which is compensated by winding the wire on the winch. The following step is to check whether the wire did not get caught in the

equipment of the shaft. The check can also be performed by using a metal ring dropped down the wire from the pit bank to the connected level or by determining the period of swing of the plummet, which can be considered mathematical pendulum. The following approximate formula applies to the period of a simple swing:

$$t \cong \sqrt{l} , \quad (12)$$

where

t - is the period of a simple swing of the mathematical pendulum [s]

l - is the length [m].

After the check, the omnidirectional prism is attached to the suspension on the connected level. For the purposes of length measurement at the pit bank, the wire is equipped with a reflective stick. Some aspects of the length measurement by means of laser telemeters on the basis of passive reflection are described, for example, in [14]. The method of length measurement using a device for an omnidirectional prism inserted coaxially is outlined in [2].

The measurement itself (swing observation) on the connected level is performed using a robotised universal measuring instrument. Given that swings will not manifest themselves at the pit bank (the movement of the wire is negligible in relation to its length), any universal measuring instrument suitable for the required measuring accuracy may be used for the measurements of the plummet position in the plumb line.

The initial points to determine the position of the plummet in the plumb line on the surface are the points on the basic orientation line (a minimum of three points) and the position of the plummet on the surface is subsequently defined using the arithmetic mean of the adjusted direction, which is calculated from the data obtained through three sets of measurements.

The station of the robotised universal measuring instrument on the connected horizon is situated on the point of the basic orientation line, from which the survey of the set of directions for the points on the basic orientation line is performed in two rounds of measurements. A part of them consists in the continual measuring of the polar coordinates of individual positions of the plummet in the swing. The measuring procedure is as follows (the first set of measurements):

1. Set the plummet swinging in one direction and survey individual positions of the plummet in the swing in the total number of 10 swings;
2. Survey the set of directions for the points on the basic orientation line in two rounds of measurements;
3. Set the plummet swinging in the direction perpendicular to the previous one and to survey individual positions of the plummet in the swing in the total number of 10 swings;
4. Survey the set of directions for the points on the basic orientation line in two rounds of measurements.

The abovementioned method is applied also to the other two sets of measurements. After the three sets of measurements with one weight are performed, the same procedure is applied in three sets of measurements to the second and the third weight.

The described measuring method requires the use of a robotised instrument equipped with the ATR (automatic target recognition) and the LOCK (prism lock) functions. It is also necessary to select the time interval between the measurements of individual positions of the plummet in the swing so that the density of the points represents adequately the trajectory of the plummet. In general, it is possible to observe that the plummet trajectory is more accurate with shorter intervals between measurements. By using an electro-optical telemeter, the impact of systematic errors is mitigated as it is possible to enter the physical reductions directly into the software of the instrument and the abovementioned effect of errors is already corrected in the measured lengths. For the purposes of further calculations, it is

necessary to correct the measured lengths to reflect also mathematical reductions, in particular the altitude correction.

Other conditions having an adverse effect on the characteristics of geodetic networks are mentioned, for example in v [16], [10], [32] and [30], the adverse effect of refraction on the estimate of the geodetic network parameters is described, for example, in [8] and in [4].

The connecting surveys and orientation measurements performed in this manner also involve the determination of the bearing of at least two points on the basic orientation line using a gyrotheodolite.

The position of the plummet in the plumb line is calculated for each set separately and is determined for individual weights as an arithmetic mean established on the basis of the data obtained through all three sets of measurements. The corrections of the position of the plummet in the plumb line as suggested by Wilski are defined for each weight and the resulting position of the plummet in the plumb line is calculated as the mean of the corrected positions of the plummet for the given weights. The measurements are processed within the local coordinate system referenced to the points on the basic orientation line.

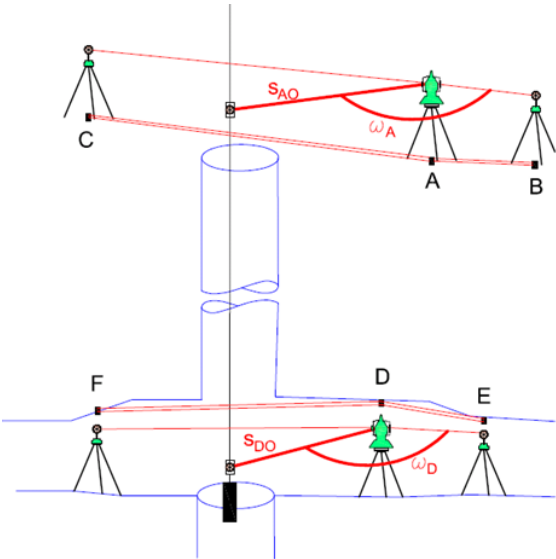


Fig. 28 Schematic sketch of connecting surveys on the surface and on the connected horizon

On the basis of the calculated coordinates of the plummet position in the plumb line, length s_{DO} between point D and the plummet position in the plumb line (see Fig. 28) are determined as well as angle ω_D between the points on basic orientation line D, E and the plummet position in the plumb line.

On the basis of bearing σ_{DE} determined by the gyrotheodolite and angle ω_D , the bearing from the projected point to point D, from which the measurement was performed, is calculated. On the basis of the bearing so calculated, length s_{AO} , lengths and angles measured on point D, the coordinates of points D, E and F on the basic orientation line are subsequently calculated. The innovated technical solution is depicted in Fig. 30.



Fig. 29 *Mine cage roof*

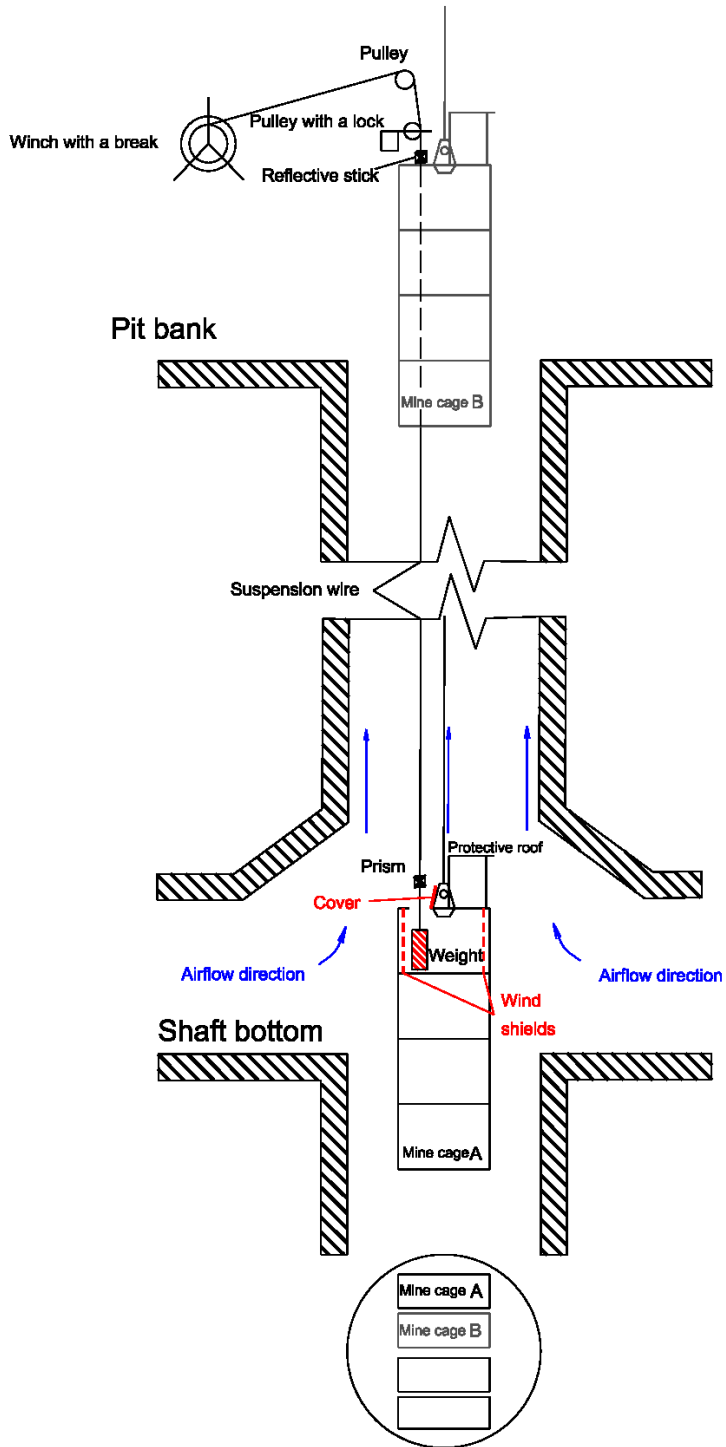


Fig. 30 *Innovated technical solution for performing connecting surveys*

5.4 Determination of swing centres for the determination of the accurate position of the plummet in the plumb line

The method of swing centre determination for the purposes of the determination of the accurate position of the plummet in the plumb line was tested in the IGDM training shaft. The shaft has the form of a 1.2 x 2.0 m rectangle and no equipment is installed in it. It is 35 m deep. The diameter of the suspension wire was 1.2mm and the weight of the plummet, above which a suspension for a omnidirectional prism was attached, was 20 kg. The tests were performed using a Leica TS 30 robotised universal measuring instrument, set to automatically register measured data at an interval of 0.3 s. A GRZ101, 360°, Mini Reflektor omnidirectional prism was inserted in the suspension above the plummet. A total of 40 observations were made (20 in one direction and 20 in the direction perpendicular to the first one). One observation involved 10 swings.

The speed of the airflow in the shaft is minimal (laminar movement). The results of individual swing trajectory measurements show that the plummet moved on a closed curve. The method described herein is based on a mathematical analysis of the individual swing trajectory measurements and determines the projection of the suspension point by calculation based on the pattern measurements. The method relies on detailed measurement of the trajectory travelled by several swings.

If we accept that during measurements, the trajectory of a mass point runs on a plane and on a closed curve, the normally used methods are based on the movement on a line, then the curve can be replaced with a conic, ellipse. Hence, a mass point will travel on an ellipse whose half-axes will be of a variable value. The value of the major half-axis will depend on the suspension length and the amount of the damping force at the suspension point, while the value of the secondary half-axis will primarily depend on the amount of lateral forces. If we are able to measure the points of the suspended mass point movements, these points can be

used to calculate the position of the focuses, sizes of individual half-axes and subsequently, with certain accuracy, determine the centre of the ellipse. If our calculations are based on several swings, it will also be possible to determine the deviation (mean error) of the position of the ellipse centre. From the perspective of statistical processing of measurement results, it is necessary to base the calculations on a minimum of five full swings. Since the beginning of the measurements cannot be in practice referenced to any clearly defined position of the mass point, the following procedure needs to be applied for mathematical processing:

- Define the points measured within one swing;
- Eliminate gross measurement errors;
- Calculate the values of the shift of the centre or the orientation and the size of the half-axes;
- Determine the ellipse centre and its absolute error;
- Determine the maximum and mean errors of the shift of the centre and, if applicable, errors of the half-axis orientation.

When determining individual swings, we need to base our conclusions on the measurement conditions and accept realistic possibilities and measurement conditions in the field. If we assume that the suspension rope is several hundred metres long and the period of one swing is thus around one minute, the measurements will take relatively long time. Moreover, the measurements need to be organised as dynamic; it is very likely that it will not be possible to define clearly the beginning of the measurements. In addition to random interferences, certain discontinuities are likely appear during measurements due to the failure of the measuring or recording instrument. The evaluation method then needs to be adjusted to take into account all these factors. The fundamental task is to assign the points measured to the corresponding swings, which is permitted by the existence of gross errors.

The general rule is that gross measurement errors occur by neglect or omission, failure of the measuring instrument, inappropriate measurement method, etc. Such errors are basically impossible to correct and measurements must be repeated in any such event. If measurements are repeated several times, the values affected by a gross error can be identified, as they clearly do not fit in the set of the measurements. Such errors therefore must be excluded from the set of the values obtained by measurement and must not be included in the processing of random errors. In the case of plummet swing measurements, a gross error means a discontinuity in the data obtained and can be used for dividing the set of data into the different swing stages. A graphical representation of the subsets then enables to identify clearly the points attributable to individual swings, based on which we can process statistically the data obtained through measurements and determine mathematically the stable position of the pendulum.

If we obtain through the measurements a set of data containing a set of points that determine the pendulum movement in a coordinate system, by connecting the points, we can draw an ellipse on which the pendulum moves. The point coordinates are related to the selected coordinate system which will not be identical with the ellipse centre, and the ellipse centre will be shifted in relation to that system. Similar considerations need to be applied to the orientation of the selected coordinate system against the half-axes of the ellipse. Therefore, in order to determine the equation of the ellipse, we cannot base our calculation on the canonical form only, but on the general equation of a conic in an oriented position:

$$a_{11}x^2 + 2a_{12}xy + a_{22}y^2 + 2a_{13}x + 2a_{23}y + a_{33} = 0, \quad (13)$$

where variables x and y represent the coordinates of the selected coordinate system. The quadratic members of the equation characterise the ellipse with the centre identical with the coordinate system, the linear members characterise the shift of the ellipse centre against the coordinate system, and the member containing the

product of variables $x.y$ characterises the orientation of the ellipse. Since the result of the measurements consists in known swing point coordinates, we must first determine coefficients a_{11} to a_{33} . Given the values obtained through the measurements, the equation can be standardised for the sake of simplicity in such a way that member $a_{33} = 1$; the equation of the ellipse is then determined by means of five points obtained from the measurements by solving the following set of equations (14):

$$\begin{aligned}
 a_{11}x_1^2 + 2a_{12}x_1y_1 + a_{22}y_1^2 + 2a_{13}x_1 + 2a_{23}y_1 + a_{33} &= 0, \\
 a_{11}x_2^2 + 2a_{12}x_2y_2 + a_{22}y_2^2 + 2a_{13}x_2 + 2a_{23}y_2 + a_{33} &= 0 \\
 a_{11}x_3^2 + 2a_{12}x_3y_3 + a_{22}y_3^2 + 2a_{13}x_3 + 2a_{23}y_3 + a_{33} &= 0, \quad (14) \\
 a_{11}x_4^2 + 2a_{12}x_4y_4 + a_{22}y_4^2 + 2a_{13}x_4 + 2a_{23}y_4 + a_{33} &= 0, \\
 a_{11}x_5^2 + 2a_{12}x_5y_5 + a_{22}y_5^2 + 2a_{13}x_5 + 2a_{23}y_5 + a_{33} &= 0.
 \end{aligned}$$

As the data obtained from the measurements are affected by an error, it is likely that not all the sets of five points will give an ellipse (i.e., the set of equations under (14) will be solvable). Given the number of data, these cases can be omitted.

After introducing the coefficients so calculated into equation (13), we will obtain a general equation of a conic for the particular conic. The equation describes the pendulum movement in the selected coordinate system. As the equation is composed of the points established by the measurements, which are affected by a random measurement error, the entire calculation needs to be repeated at least five times with different coordinates of the ellipse points obtained through measurements. The position of the pendulum so measured must therefore be described by a minimum of 30 different points. Repeated calculations of the set of equations under (14) render up to five values for each coefficient a_{11} to a_{33} , from which we can determine mean values $\overline{a_{11}}$ to $\overline{a_{33}}$ and the corresponding most probable errors (corrections) $v_{a_{11}}$ to $v_{a_{33}}$ based on the general relations:

$$\bar{a} = \frac{\sum_{i=1}^n a_i}{n} \quad \text{and} \quad v_{a_i} = \frac{\sum_{i=1}^n |a_i - \bar{a}|}{n-1}, \quad (15)$$

where n is the number of the calculations (measurements), i.e., in this case $n=5$. The following equation then applies to the individual coefficients generally:
 $a_i = \bar{a} + v_{a_i}$.

The general form of equation (13) is:

$$\bar{a}_{11}x^2 + 2\bar{a}_{12}xy + \bar{a}_{22}y^2 + 2\bar{a}_{13}x + 2\bar{a}_{23}y + \bar{a}_{33} = 0, \quad (16)$$

which describes the ellipse in the selected coordinate system and accepts random measurement errors. A graphical representation of the coordinate systems is shown on Fig. 31.

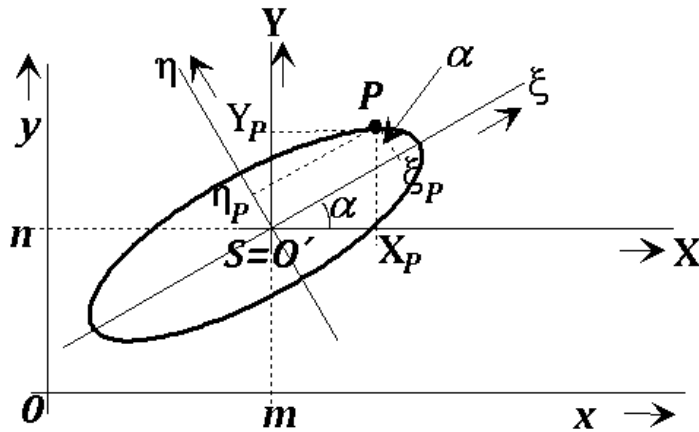


Fig. 31 Representation of the coordinate systems of the error ellipse

To identify ellipse centre S with the beginning of the coordinate system, we need to transform selected coordinates x and y into a new, shifted system beginning in point $O'[m, n]$, where m and n indicate the shift at the different axes. The shift can be defined by the following relations:

$$x = X + m, \quad a \quad y = Y + n. \quad (17)$$

When introducing the relations under (17) to the equation under (16), we obtain the following adjusted formula:

$$X^2[\overline{a_{11}}] + X[2\overline{a_{11}}m + 2\overline{a_{12}}n + 2\overline{a_{13}}] + Y^2[\overline{a_{22}}] + Y[2\overline{a_{12}}m + 2\overline{a_{22}}n + 2\overline{a_{13}}] + XY[2\overline{a_{12}}] + \overline{a'_{33}} = 0, \quad (18)$$

where

$$\overline{a'_{33}} = \overline{a_{11}}m^2 + 2\overline{a_{12}}mn + \overline{a_{22}}n^2 + 2\overline{a_{13}}m + 2\overline{a_{23}}n + \overline{a_{33}}. \quad (19)$$

Since $S[m, n]$ applies to the ellipse centre, the centre is at the beginning of the new coordinate system $O'[m, n]$, which is shifted in relation to the selected coordinate system by values m, n , the coefficients of the linear members must equal to zero, and therefore the following equations apply:

$$\begin{aligned} \overline{a_{11}}m + \overline{a_{12}}n + \overline{a_{13}} &= 0 \\ \overline{a_{12}}m + \overline{a_{22}}n + \overline{a_{23}} &= 0. \end{aligned} \quad (20)$$

The solution of the set of equations under (20) produces the values of the shift of the centre of the new, deflected coordinate system, and the following equations apply:

$$m = \frac{\overline{a_{12}} \overline{a_{23}} - \overline{a_{13}} \overline{a_{22}}}{\overline{a_{11}} \overline{a_{22}} - \overline{a_{12}} \overline{a_{21}}}, \quad (21)$$

$$n = \frac{\overline{a_{13}} \overline{a_{12}} - \overline{a_{11}} \overline{a_{23}}}{\overline{a_{11}} \overline{a_{22}} - \overline{a_{12}} \overline{a_{21}}}. \quad (22)$$

The equation of the ellipse having its centre in point $S \equiv O'$ has the following form in the shifted coordinate system:

$$\overline{a_{11}}X^2 + 2\overline{a_{12}}XY + \overline{a_{22}}Y^2 + \overline{a'_{33}} = 0. \quad (23)$$

It is clear that the coefficients of the quadratic members do not change as a result of the shift of the coordinate system.

The following relations can be applied to the calculation of mean shift errors:

$$\begin{aligned} m_m^2 = & \left(\frac{\partial m}{\partial a_{11}}\right)^2 m_{a_{11}}^2 + \left(\frac{\partial m}{\partial a_{12}}\right)^2 m_{a_{12}}^2 + \left(\frac{\partial m}{\partial a_{13}}\right)^2 m_{a_{13}}^2 + \left(\frac{\partial m}{\partial a_{22}}\right)^2 m_{a_{22}}^2 + \\ & \left(\frac{\partial m}{\partial a_{21}}\right)^2 m_{a_{21}}^2 + \left(\frac{\partial m}{\partial a_{23}}\right)^2 m_{a_{23}}^2 \end{aligned} \quad (24)$$

$$\begin{aligned} m_n^2 = & \left(\frac{\partial n}{\partial a_{11}}\right)^2 m_{a_{11}}^2 + \left(\frac{\partial n}{\partial a_{12}}\right)^2 m_{a_{12}}^2 + \left(\frac{\partial n}{\partial a_{13}}\right)^2 m_{a_{13}}^2 + \left(\frac{\partial n}{\partial a_{22}}\right)^2 m_{a_{22}}^2 + \\ & \left(\frac{\partial n}{\partial a_{21}}\right)^2 m_{a_{21}}^2 + \left(\frac{\partial n}{\partial a_{23}}\right)^2 m_{a_{23}}^2 \end{aligned} \quad (25)$$

If we want to determine the sizes of the individual half-axes of the ellipse, the shifted coordinate system $[XO'Y]$ needs to be orient in such a way that the new axes ξ and η lie at the axes of the ellipse. Based on such orientation, we can determine the specific orientation angle α . For the purposes of the orientation of the system, Fig. 31 can be translated into the following formula:

$$\begin{aligned} X &= \xi \cos \alpha - \eta \sin \alpha, \\ Y &= \xi \sin \alpha - \eta \cos \alpha. \end{aligned} \quad (26)$$

After the relations described in (26) are introduced in the equations under (24) and (25) and then adjusted, the following equation applies:

$$\begin{aligned} & \xi^2 [\overline{a_{11}} \cos^2 \alpha + 2\overline{a_{12}} \cos \alpha \sin \alpha + \overline{a_{22}} \sin^2 \alpha] + \xi\eta [-2\overline{a_{11}} \cos \alpha \sin \alpha + \\ & 2\overline{a_{12}} \cos^2 \alpha - 2\overline{a_{12}} \sin^2 \alpha + 2\overline{a_{22}} \sin \alpha \cos \alpha] + \eta^2 [\overline{a_{11}} \sin^2 \alpha - \\ & 2\overline{a_{12}} \sin \alpha \cos \alpha + \overline{a_{22}} \cos^2 \alpha] + \overline{a_{33}} = 0. \end{aligned} \quad (27)$$

Since once the coordinate system is orient by angle α , the half-axes of the ellipse will lie at the axes of the orient coordinate system, the value of the member in the brackets of product $\xi.\eta$ will be zero, hence:

$$[-2\overline{a_{11}} \cos \alpha \sin \alpha + 2\overline{a_{12}} \cos^2 \alpha - 2\overline{a_{12}} \sin^2 \alpha + 2\overline{a_{22}} \sin \alpha \cos \alpha] = 0. \quad (28)$$

The subsequent adjustment will give the following equation:

$$\begin{aligned} \tan \alpha &= \frac{(\overline{a_{22}} - \overline{a_{11}}) \pm \sqrt{(\overline{a_{22}} - \overline{a_{11}})^2 + 4\overline{a_{12}}^2}}{2\overline{a_{12}}}, \\ \alpha &= \arctan \frac{(\overline{a_{22}} - \overline{a_{11}}) \pm \sqrt{(\overline{a_{22}} - \overline{a_{11}})^2 + 4\overline{a_{12}}^2}}{2\overline{a_{12}}}. \end{aligned} \quad (29)$$

As angle α is calculated on the bases of the mean values of coefficients $\overline{a_{11}}$ to $\overline{a_{22}}$, the result naturally is the mean value of the angle. The mean error of angle α can then be calculated as follows:

$$m_{\alpha}^2 = \left(\frac{\partial \alpha}{\partial a_{11}} \right)^2 m_{a_{11}}^2 + \left(\frac{\partial \alpha}{\partial a_{12}} \right)^2 m_{a_{12}}^2 + \left(\frac{\partial \alpha}{\partial a_{22}} \right)^2 m_{a_{22}}^2 \quad (30)$$

The squares of the individual half-axes can be calculated on the basis of the relation defined under (27) as:

$$\begin{aligned}\bar{a}^2 &= \bar{a}_{11} + 2\bar{a}_{12} \tan \alpha + \bar{a}_{11} \tan^2 \alpha \\ \bar{b}^2 &= \bar{a}_{22} + 2\bar{a}_{12} \tan \alpha + \bar{a}_{22} \tan^2 \alpha.\end{aligned}\quad (31)$$

Their values can then be determined following the extraction of the root. The mean errors of the sizes of the half-axes are:

$$\begin{aligned}m_a^2 &= \left(\frac{\partial a}{\partial a_{11}}\right)^2 m_{a_{11}}^2 + \left(\frac{\partial a}{\partial a_{12}}\right)^2 m_{a_{12}}^2 + \left(\frac{\partial a}{\partial \alpha}\right)^2 m_\alpha^2 \\ m_b^2 &= \left(\frac{\partial b}{\partial a_{22}}\right)^2 m_{a_{22}}^2 + \left(\frac{\partial b}{\partial a_{12}}\right)^2 m_{a_{12}}^2 + \left(\frac{\partial b}{\partial \alpha}\right)^2 m_\alpha^2.\end{aligned}\quad (32)$$

The procedure described above is utterly general; however, it is not capable of accepting all the connections affecting the accuracy achieved in determining the ellipse centre, e.g., the calculation does not take into account the length of the suspension rope. The course of the measurements can also be affected by the period of duration of one swing. For the sake of the measurement and minimisation of random measurement errors, it is therefore advisable to record as large number of points in one swing as possible and to determine coefficients a_{11} to a_{33} of the set of equations under (14) for as large number of the points measured as possible. Generally, all points of one swing can be used in the solution of the set of equations under (14).

From the practical point of view, it is convenient to choose such points that will produce the maximum value of each half-axis, as the calculation error will be smaller than if the value of the half-axis were zero. The dependence between the maximum value of half-axes a_{max} and b_{max} and the point coordinates can be established upon an examination of the canonical form of the equation of the ellipse under (33), i.e., based on the calculation of the first-order derivatives of this equation using variables a and b .

$$\frac{(x-m)^2}{a^2} + \frac{(y-n)^2}{b^2} = 1. \quad (33)$$

By letting the first-order derivatives calculated on the basis of the individual variables of the above equation go to zero, the following applies:

$$\begin{aligned} a_{max} &= x - m, \\ b_{max} &= y - n, \end{aligned} \quad (34)$$

which means that the higher is the value of point x and y , the larger is the size of the half-axes. For the purposes of calculations, it would therefore be optimal using swing points around the maximum (or, as a result of the shift of the centre, minimum) values of coordinates x and y . Given the nature of the curve, however, the value of the point with coordinate x_{max} as well as of that with coordinate x_{min} is $y=0$ and vice versa. For this reason, it is advisable to use the points of the entire swing, which are equally distributed. In a complex calculation, it would also be advisable accepting the results of several separate swings.

Given the organisation of the entire measurement, it is impossible to measure individual swings separately and it is necessary to identify individual swings in the set of data so measured, separate individual swings from each other and make separate calculations for each swing in the first stage. In the second stage of the calculus, we then need to express in statistical terms the values of the shifts of the ellipse centre in individual swings. When adopting this approach, we can apply standard statistical methods for processing the data obtained through the measurements, including the determination of the mean error or the error of the arithmetic mean of the measurements. If necessary, it is then possible to define the mean and maximum error, or the deviation for n independent measurements, to which generally known relations apply (see Chapter **Chyba! Nenalezen zdroj o dkazů.**).

The procedure described above was applied to the data obtained experimentally during connecting surveys performed for the purposes of the

envisaged connecting underground crosscut between the ČSA 2 and Mír 5 shafts in the Karviná part of the Ostrava-Karviná Coal District.

5.5 Determination of swing centres using a robotised universal measuring instrument and a graphical solution

A suspension for coaxial insertion of a surveying prism in the plummet suspension is used to observe plummet swings in connecting surveys (see Chapter 5.1).

Measurements can be performed either from a point on the basic orientation line or from a station selected arbitrarily so that the position of the instrument guarantees good visibility of the surveying prism within the entire range of plummet swings. Measurements carried out from a point on the basic orientation line are more appropriate for the calculations of the coordinates of the other points on the basic orientation line as provided below. When opting for a station outside the points on the orientation line, it is advisable that we have visibility of all points on the basic orientation line.

In cases where visibility between the station and the points on the basic orientation line cannot be achieved, it is more difficult to process the measurement results afterwards. This can be resolved by the calculation of oriented lengths or by the calculation of a micronetwork. The points on the basic orientation line are calculated in the local coordinate system.

Before swing measurements are carried out, it is first necessary to survey the lengths and the set of directions in two groups in relation to the points on the basic orientation line. This procedure is repeated after the observations of each series of plummet swings are terminated.

5.5.1 Swing measurements using a robotised universal measuring instrument

Before performing the measurements, we first need to set the telemeter. This involves setting the following functions:

- LOCK (prism observation) – this function allows observing the prism. The Leica TS30 can observe a prism moving in a distance of 20 m and at the speed of $9 \text{ m}\cdot\text{s}^{-1}$ in the horizontal direction and $5 \text{ m}\cdot\text{s}^{-1}$ in the vertical direction.

- Low visibility (poor visibility) – this enhances the automatic focus function of the instrument in poor climatic and visibility conditions. Setting the low visibility function in mines is necessary. Otherwise, measurements are often interrupted and the final swing trajectory is only partial.

- SynchroTrack – this is a mode for interpolation of angle measurements using the LOCK function. This interpolation method enhances the accuracy of the values obtained through measurements for all dynamic applications (e.g., machine guidance).

- Additionally, it is necessary to set the measurement speed of the individual points in the automatic measurement mode. The TS30 enables automatic point measurements at the minimum interval of 0.3 s.

At this stage, it is necessary to focus the instrument on the prism and start point measurement. The instrument then automatically measures individual plummet swings and records the following data regarding the individual points: point number, horizontal angle, zenith angle, distance, and time. The data so obtained can be easily downloaded to a computer for subsequent processing.

5.5.2 Graphical processing and evaluation of data

On the basis of the data obtained through the measurements, we will calculate the coordinates of the points describing the swing trajectory in the local coordinate system.

Given the accuracy of the instrument used and for the sake of better description of the ellipse and the subsequent mathematical calculation of the ellipse

centres, the point coordinates need to be stated in metres rounded off to four decimal places. Fig. 32 shows the connecting lines of the points and their coordinates in millimetres (in black), in tenths of millimetres (in red) and a graphically determined ellipse (in blue). The figure demonstrates that the final ellipse better corresponds to the points whose coordinates were rounded off to four decimal places.

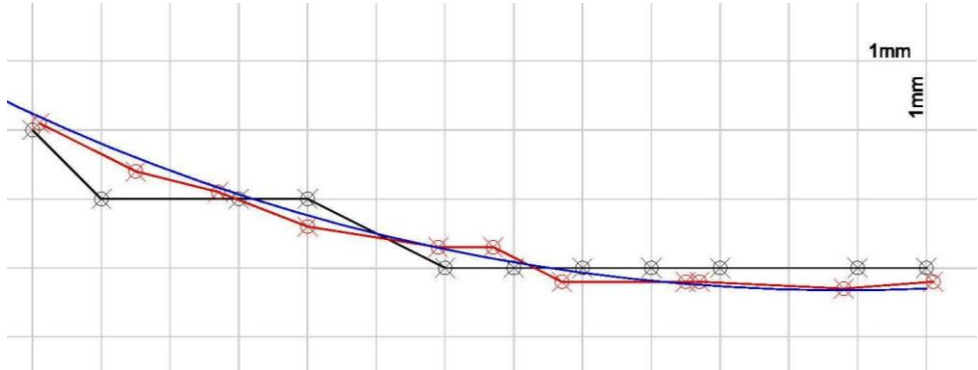


Fig. 32 *Connecting lines of the points and a graphically determined ellipse*

Upon graphical evaluation of the swings, we first need to connect the points surveyed and describe the trajectory of the plummet swings. For this, we use the AutoCAD software, enabling to automatically draw the curve (the “curve” command) from the coordinates entered in the text format. The “curve” command requires the use of a decimal point, with a comma being the separator of the x, y coordinates.

In view of the large number of the connected points, the automatic curve drawing function helps to speed up the work significantly. Fig. 33 shows the entire set of data from one connected level (approx. 6,500 points). During the first attempts at swing evaluation, curves were drawn manually, which was very time consuming.

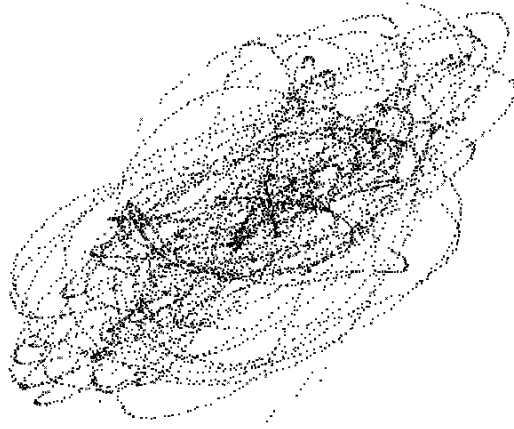


Fig. 33 *Graphical representation of a set of points from one connected level*

Individual swings can best be replaced by an ellipse. For the subsequent processing, it is necessary to split the curve into individual parts resembling ellipses, see Fig. 34.

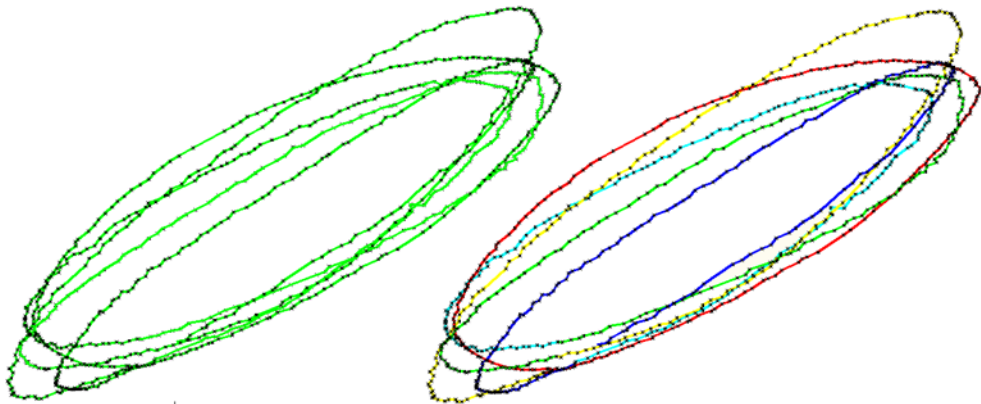


Fig. 34 *Individual swings replaced by an ellipse*

The swing centre is determined as the centre of the ellipse which best corresponds to its trajectory. It is necessary to pay adequate attention to drawing the ellipse.

Based on our experience, an ellipse should be drawn in accordance with the following principles:

- The ellipse should have minimum deviations from the swing pattern;
- The ellipse should touch the curve only at its vertices;

- The deviations of the ellipse should be compensated in the swing pattern;
- We should prefer that the osculating circles of the ellipse touch the swing pattern.

Ellipses can be placed differently, but if we adhere to the principles defined above, deviations of the ellipse (swing) centres are minimal. An example is shown in Fig. 35. The swing pattern is shown in light blue, with ellipses drawn in accordance with the principles outlined above being illustrated in blue and red. The deviation of the ellipse centres is 0.3mm. If the ellipse was drawn inaccurately (as shown in green), the deviation of its centre would be 1.6 mm.

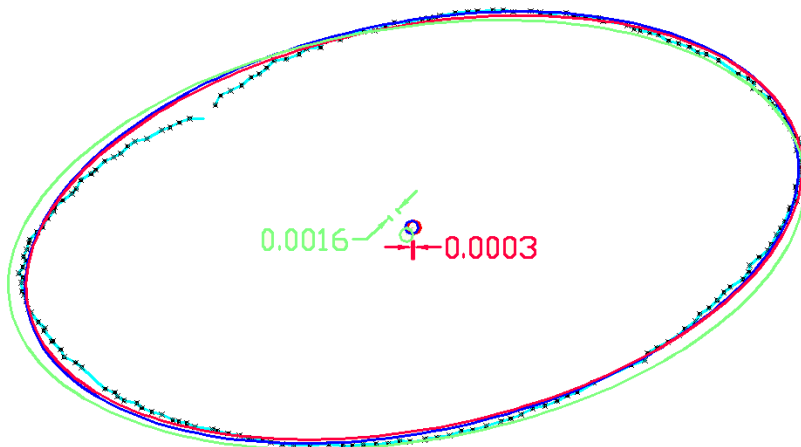


Fig. 35 *Deviations of ellipse centres*

This procedure is then applied to processing all swings, and the projected point (shown in violet) is determined as the arithmetic mean of the centres of individual ellipses, see Fig. 36.

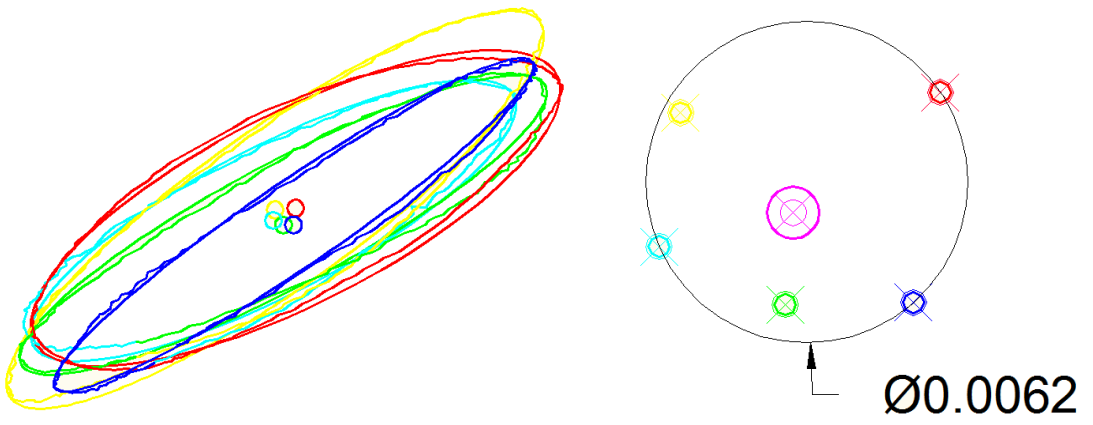


Fig. 36 *Arithmetic mean of swing centres*

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