USE OF SATELLITE GPS TECHNIQUE IN THE MEASUREMENTS OF DEFORMATIONS IN THE AREAS OF MINING EXPLOITATION

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Abstract

Deformation measurements in the areas subdued to mining exploitaton are very important for the protection of the objects and the surface of these areas. An obstacle in achieving a satisfactoty accuracy of these measurements was made by the difficulties in finding constant reference points and inaccuracies of geodesic canvass. Owing to the inroduction of satellite technology and the application of precise electronic instruments it is possible to achieve subcentimeter level accuracies in the determination of the localization and height of observed points. In the article results of survey and experiments concerning the measurement of deformation in the mining area of the Salt Mine in Wieliczka near Cracow (Kraków) were presented. Achieved results prove great opportunities of the use of satellite measurements and total station instruments to determine post- exploitaton deformations of the area.

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1. Introduction

New measurement technologies introduced into geodesy in recent years, especially satellite techniques and modern precise electronic instruments (such as total stations), as well as the development of computer data analyses and processing makes it possible to introduce new ways of the measurement of deformations in the areas under the influence of mining exploitation. As we know, deformations of the surface are characterized by giving the values of respective indexes, including: subsidence (vertical dislocation), horizontal dislocation, horizontal deformation (sometimes even vertical deformation), inclination and curvature. Apart from the two latter indexes, usually calculated in indirect way, other values are usually obtained directly from the results of geodetic observations. Compared to other values, subsidence is the easiest to determine. It is determined with a great accuracy (in case of precise leveling). Also horizontal deformation is determined without difficulties through the comparison of the distances between points measured in subsequent measurement series. So far the most difficult index to determine has been horizontal dislocation; methods of measurement, even with the use of precise electronic instruments have not been giving accurate enough results, because of the errors of reference points.

Basic problem in the measurement of deformation in mining areas made finding constant reference points of a proper accuracy. For the height measurements, the purpose of which was to determine the subsidence of the area, this task did not cause greater problems, although the length of the control traverse influenced the accuracy of the observation. Considerable difficulties resulted when it was necessary to determine horizontal dislocation; errors in the control network, its heterogeneity, as well as uncertainty in the stability of the points caused the decrease in the quality of obtained results. Because of that the observations to determine horizontal dislocations were run rarely, usually the measurements of distances in observation lines were found satisfactory and based on this horizontal deformations or dislocations along the lines were measured.

The use of modern technologies of observations and precise instruments allows to:

- determine the coordinates of points with the accuracy of a few millimeters (based on satellite observations); this reduces the problem of net reference to finding points that would be convenient for the satellite observations in the examined area;
- make precise angular-linear and leveling measurements between satellite reference points to determine flat and height coordinates in an adopted system, and – through the comparison of the results from the subsequent observation series – define horizontal and vertical dislocations and deformations.

One of the areas, subdued to surface deformations is the town of Wieliczka and its environs. The town has 18 thousand residents. It is in south-east Poland, 15 km from Kraków (Cracow). There is the most famous in Poland and one of the most famous in Europe old, originating from 13th century salt mine in Wieliczka. Till 1995 salt mining was going on there, which made this mine one of the longest exploited mines in the world. There is a permanent exhibition in the mine, showing the development of salt mining and work of miners over the centuries of mine's existence. Unique character of the mine, the only such place in Europe caused listing the Wieliczka mine into the first UNESCO list of World Culture Heritage.

Choosing Wieliczka region to carry out the research was specially justified by its particular location and the combination of different geodynamic (natural and anthropogenic) processes. This region is on the periphery of the Carpathian Mountains in the place of their closest contact with the Central European Platform, while on the Wieliczka meridian main tectonic faults of the Carpathian Mountains come together. The location of the town in the contact of those two structures is connected with the instability of the rock mass, including neotectonic movements of the Carpathian Mountains, relatively frequent, considering Polish conditions tectonic quakes, as well as the influence of the process of the tightening of old workings caused by centuries-long exploitation of mineral salt. These processes cause changes in water balance, which stimulates the formation of landslides on the slopes of the Wieliczka Valley, as well as causes deep suffosion, making threat both to the mining workings and to the surface together with the objects situated there.

In the region of Wieliczka the following processes, causing changes in surface morphology can be defined:

- tectonic movements, connected with dislocations of platforms, post-glacial decompression and local tectonics of the Carpathian Mountains;
- technogenic movements caused by the mining exploitation for centuries;
- landslide movements, mainly natural, sometimes caused by mining activities;
- movements caused by the changes in water balance in the rock mass, including water suffosion.

2. Survey of the Surface Deformation in the Wieliczka Region

Deformations and geomorphological changes detected on the surface of the area, already in 1926 made researchers carry out geodetic observations. The network established that time was then extended over the following years. To define the size of horizontal and vertical surface dislocations in 1990s ten meridional observation lines and one parallel line was established in the mining area of Wieliczka. Distal points of these lines were situated out of the range of exploitation influence. The lines were supplemented by the network of points in the region of water leakage into the gallery "Mina" and in the region of drilling exploitation of salt in Barycz. The network covered more than 1200 points altogether, when nearly 800 were subdued to series angular-linear and height observations, remaining points – only to height measurements. On nine levels of the mine about 150 underground bench-marks were stabilized.

Basic problem in defining the scale of the deformation was proper reference of the network. For the horizontal canvass in the region of Wieliczka are heterogeneous and errors in the location of marks are considerable. Moreover, individual fragments of the canvass, established in different years by different persons are dislocated up to ±0.2 m in the relation to one another. As the result heterogeneous observation network was obtained, where accuracy of mark determination varied, which made the interpretation of observed dislocations more difficult. Height reference was achieved with greater accuracy, the mean error of height determination was (in precise leveling) ±2.0÷3.0 mm, which can be considered enough for the purpose of deformation investigations. However also in this case the heterogeneity of leveling network made it necessary to refer only to a small number of permanent bench marks or even one-bench-mark reference. Obtaining satisfactory accuracy of reference became possible when satellite measurements were introduced.

3. The Characteristic of a Research-Observation Network

To examine the results of the changes in the surface morphology resulting from the mentioned above processes, in 1994 a network of geodetic resistance points, located outside the mining area was designed. These point were located in a way that was useful for the GPS measurement (open horizon, easy access). They make two rings around the mining area. Five points of the first ring are in the distance up to a few kilometers from the borders of the mining area. Apart from this, on the hills surrounding the Wieliczka Valley from the southern part, in the framework of the research project, three so-called age points were established. The task of these points was first of all making a canvass for the observation of orogenic movements, connected with ages-lasting dynamism of the Carpathian Mountains and the location of Wieliczka in the periphery of this mountain system. These points were established in such a way that they could be used many times. The stabilization scheme was presented in Fig. 1.

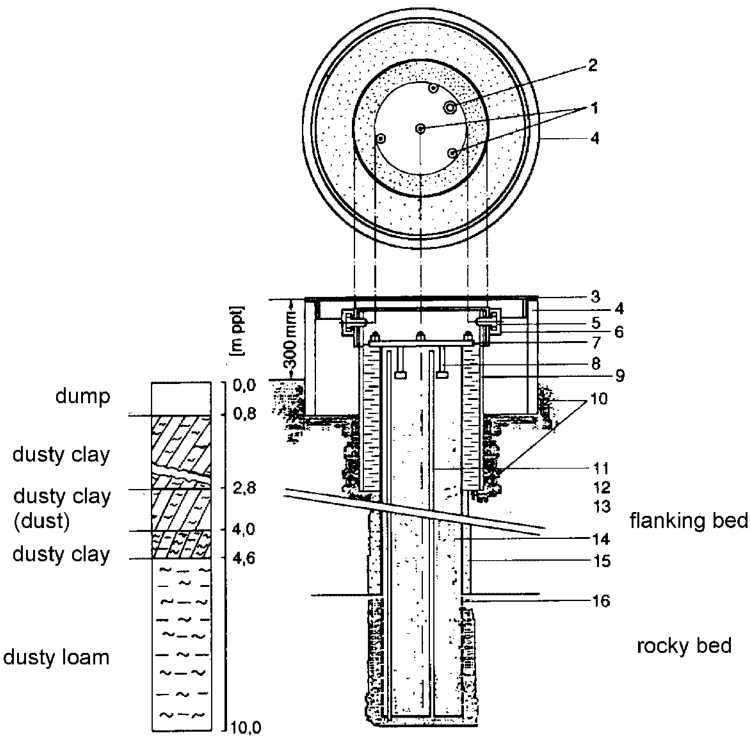

Fig. 1. The way of stabilizing age points together with geologic profile in the place of establishing leveling bench-mark WIEA (1. Head of leveling bench-mark with stems. 2. circular spirit level. 3. Steel cover. 4. Concrete shield. 5. Securing screws. 6. Steel protective hood of leveling bench-mark. 7. Complete head of leveling bench-mark. 8. Steel nails fixing head in concrete. 9. Conductor pipe. 10. Fixing in concrete. 11. Fortifying rods. 12. Insulation from freezing. 13. Steel pipe of leveling bench-mark. 14. Filling of the pipe. 15. Sand cover. 16. Perforation of the bottom part of the pipe to bind it to the ground.

A ten meters long concrete pillar made the base for the head of the point. It was located in tight Tertiary formations. The location of points was selected based on the map of the thickness of these formations. The head contains the main mark and three additional marks allowing to define with the method of precise leveling possible inclinations of the slope. The points were protected from weather influence and from intentional or unintentional destroying by a special shield.

In the distance of several kilometers from Wieliczka the second (external) ring of resistance points was designed. There were also five points in it. The sketch of the location of resistance points of two rings was presented in Fig. 2. The points of both rings were referred to POLREF network, a fragment of the European network of satellite points EUROREF. The measurement was made with the use of Wild-Leica receivers and then this network was measured with ASHTECH MD-XII receivers. The measurement sessions lasted 1 ÷1.5 hour, signal integration was 15 s. The observations of the network were analyzed by a computer program PRISM2. Mean error of the situation of the point of the resistance network did not exceed ±3 mm (on average ±1.5÷2.0 mm). This result, referring to the internal accuracy of the network is comparable to other results around the world (Ananga et alt. 1994).

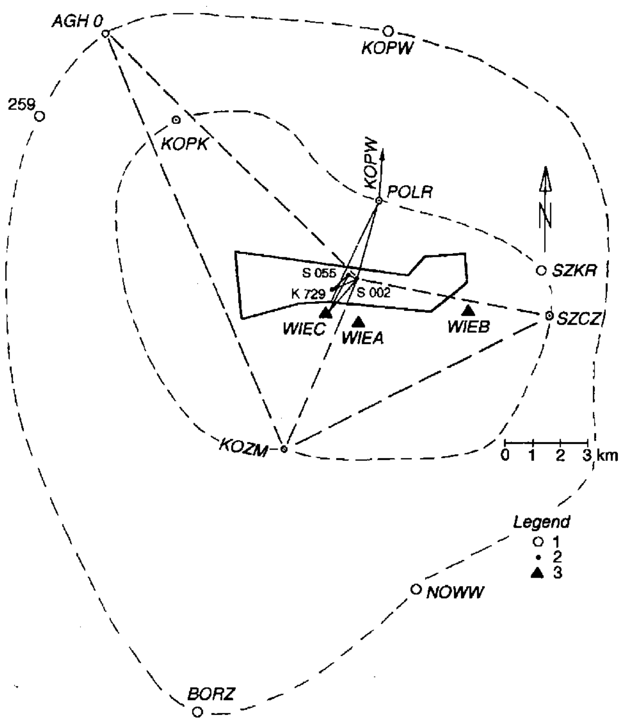

Fig.2. Sketch of the network of GPS resistance points in the surrounding of the mining area of the Salt Mine Wieliczka (1. resistance points, 2. moved points, 3. age points)

4. Calculation and Analysis of the Results from the Observation of the Network and Observation Lines

To the measured network of resistance points angular-linear measurements of the observation lines were referred. An example of such a procedure is the measurement of the observation line "Kościuszko" of a total length of 2.7 km, counting 66 points. The measurement of the line was measured by a precise total station T2002 and distance meter Di2002 with the mean error of an angle $\pm 5^{cc}$ and the length ±1 mm. The calculation of the coordinates of the lines was done based on age point WIEC on the south and three points on the north end of the line, the coordinates of which were determined from satellite observations; moreover - from those observations the coordinates of two points in the middle of the line were determined. This created the possibility of making optional adjustment, depending on the acceptation of stability of the reference points.

Altogether 12 such options were defined, every time the adjustment of the lines was made with the use of GEODEZJA program pack. The reduction of the length on the ellipsoid level was taken into account. The calculations were done in two systems of coordinates: the one accepted during the adjustment of the resistance network in Gauss-Krüger's system and in local Wieliczka system. Results of the adjustment for the respective options were evaluated based on experimental accuracy characteristics, in particular: mean error of the location of the point, mean error of the azimuth as well as mean and maximum value of length and angular corrections. For the adjustment in Gauss-Krüger's system, assuming the stability of extreme points mean value achieved for the location error of the point after adjustment was ±1.0 mm (maximum value ±1.3 mm), while considering errors of reference points it was ±3 mm. Accepting the stability of all the points of satellite observations increases this error up to ±6.6÷9.4 mm; this difference can be explained by two months' gap between the determination by GPS and angular-linear measurements; points in the middle of the line remained under the influence of mining deformations during that period.

During the adjustment of measurements in the Wieliczka system difficulties connected with the lack of information on the parameters of this system (established in 19^{th} century) arose. Adjustment with the reduction of length to the ellipsoid level causes considerable errors (up to ±52 mm) in the location of the points, that would indicate different reference level. Because of that, in the framework of the calculations made - the optimal way of the reduction of length was sought - to minimize the location errors after the adjustment. The awaited result was obtained assuming that the surface of the transformation of the system is spheroid, lying on the altitude of 278 m above the surface of an ellipsoid (Banasik et alt. 1997). With this assumption and after making adequate reductions the mean value of mean error of the point location was obtained (for the identical option as in Gauss-Krüger system), equal ±1.5 mm (maximum value ±1.8 mm). After considering the errors of reference points it was on average ±3.2 mm, maximum up to ±5.0 mm.

Carrying out the measurement of lines in an integrated network allowed to determine (after considering the differences in reference) horizontal dislocations of the line points, compared to the previous measurement. Errors in coordinates determination from the satellite measurement are almost identical with the location errors of the points of the lines after adjustment, which indicates integrity in accuracy of the GPS observations and precise angular-linear observations provided appropriate reductions and corrections (usually not taken into account during less accurate classical measurements) are introduced.

5. Looking for the Possibility of Monitoring the Movement of a Point

To define the possibility of monitoring deformations of the points and defining the character of the movement, in 1995 an experiment was run, where the GPS observation of forced horizontal movements of the point was made. To do this, above one of the points in the observation network (S002) an aerial of GPS receiver on a cross leveling head enabling fluent movements of an aerial in two mutually perpendicular directions (with the accuracy of dislocation reading ±0.1 mm). During the first measurement session the aerial was centered exactly above the point, during the following session – it was moved by the value ΔN=10 mm northwards and by ΔE = 10 mm eastwards; so the moved point was in the distance of 14.1 mm w north-eastwards compared to the initial point. The scale of the movement was approximately equal to the error that can occur in two subsequent GPS measurement sessions. To make the measurement three Ashtech MD-XII receivers were used. The experiment was repeated with other situation of receivers on resistance points. The coordinates of resistance points are characterized by mean location error ±3 mm and are outside the mining area of Wieliczka. In subsequent stages of adjustment a result characterized by the deviation from the real value not exceeding ± 1mm:

ΔN = 10.0 mm, ΔE = 9.0 mm (Góral et alt., 1995a).

During the measurements of GPS signals on the points showing a considerable dynamic of the movement a constant of rapid change in their location can occur. Thus a problem with defining the character, size and moment of dislocation arising, with GPS technology appears. It is possible to solve this task, although it involves considerable means. During the measurement at least 4-5 receivers of GPS signals are necessary, while 3-4 should be placed on the points of resistance network and the rest - on the monitored points. The latter should be inside a triangle or quadrangle, marked by the applied resistance points. Collected measurement material (realized during several or several dozen hours time interval) should be divided into 1-2-hour measurement sessions, then in a preliminary data postprocessing a set of vector components, defined by the measurement points, together with accuracy characteristic is obtained. Obtained data can be used to look for the dislocation signals. The indicator of the occurrence of the dislocation of a monitored point can be the observation that mean errors of monitored shorter vectors are higher than , że mean errors of longer vectors, made by resistance points.. Also sight analysis of residua allows to define the time moments, when systematic factors, disturbing the measurements appeared. Based on the course of the residua one can conclude if a particular displacement is only temporary or makes a linear function of time. Knowing the moments of the appearance of displacements one can use them as the moments of the beginning of new measurement sessions. Sessions obtained in such away are once again subdued to postprocessing. The results of such an analysis will allow to determine the influence of the disturbance on the changes of the coordinates of monitored points.

6. Determining Functions of Local Undulation of a Nivelation Quasigeoid

In order to determine the height of points a measurement of a considerable fragment of a network was done with the method of precise leveling with the use of a self-leveling precise leveler KoNi 007 and three meters long precise measuring rods with an invar tape and both-sides description of a code leveler NC2000 with precise rods.

Processing the results of GPS signals allows to obtain geodesic coordinates B, L and h of each point in a geocentric reference system, when h – means ellipsoid height over the surface of an ellipsoid accepted in Europe WGS-84 (GRS-80). During geometric leveling normal heights H, measured from leveling the quasigeoid are obtained. Between the quasigeoidą and ellipsoid height differences occur; the gap between them is called undulation of the quasigeoid (N). For a given point, neglecting the influence of the inclination from perpendicularity (this influence does not exceed ± 1 mm), the following relationship is obtained:

$$h = N + H \tag{1}$$

To determine a normal height H based on h value, determined from GPS measurements, one should define the distance of the gap of the quasigeoid from ellipsoid N. In practice it is easier to determine differences Δh and ΔH for two selected points P_i, P_j and based on this calculate the undulation difference ΔN, which can be written as follows:

$$\Delta N_{ij} = \Delta h_{ij} - \Delta H_{ij} \tag{2}$$

Thus when defining in a selected area - based on GPS measurements - differences of elipsoid heights Δh between individual reference points and differences of normal heights with the use of geometric levelling, as a result one obtains the differences in the undulation of quasigeoid ΔN. Depending on the size of an examined area the function of these differences ΔN can be approximated by the equation of a flat, spherical or ellipsoid surface, receiving function ΔN (B, L, B_0, L_0), where: B and L – mean geodesic width and length of a given point and B_0 and L_0 – geodesic coordinates of a reference point determined based on the processing of GPS measurements. This function can be used to calculate function ΔH (B, L, B_0, L_0), using Δh value (B, L, B_0, L_0), defined based on GPS measurements. The following transformation of the formula (2) is obtained:

$$\Delta H = \Delta h - \Delta N \quad (3)$$

Within the research, with the help of leveling measurements and by the GPS method the heights of age points and twelve other points of the network were determined. As a result of the analysis of GPS measurements and the results of leveling measurements the opportunity of the approximation of function ΔN in the mining area of Wieliczka and its vicinity was gained. The course of this function in the mining area of Wieliczka and its vicinity was presented in the form of an isoline in Fig. 3.

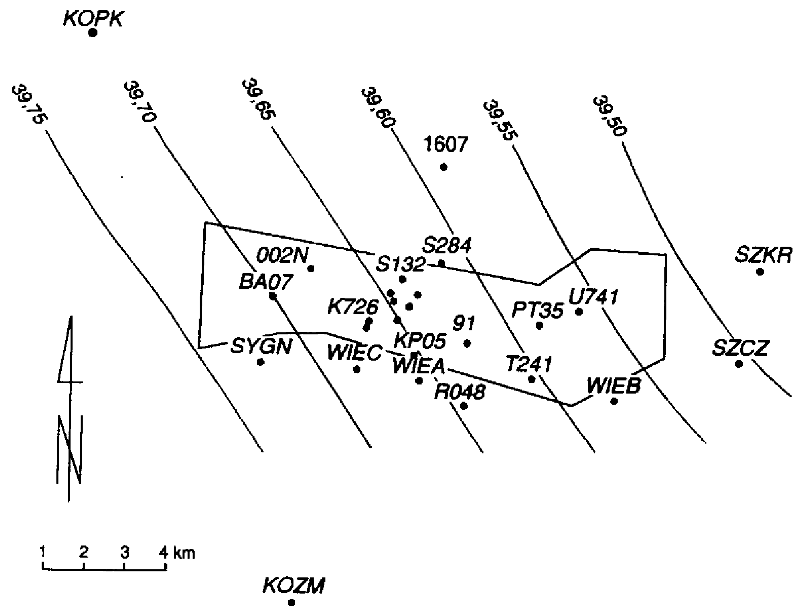

Fig. 3. Isolines of the undulation between WGS 84 ellipsoid and a levelling quasigeoid in the Wieliczka region.

To define the way of referring the network to the points, the heights of which were determined by using GPS technique, the analysis of eight options of the models approximating the function of the difference of geoid undulation ΔN. The options varied in the assumption of the stability of individual points and the kind of approximation (flat or ellipsoid). During further analysis individual options were defined based on the mean value of bias from the results of precise leveling, selecting optimal option (maximal height bias: ±4.2 mm, mean bias: ±2.3 mm). It was stated that all the flat approximation options showed smaller compatibility with the results of precise leveling than the results of ellipsoid approximation.

As the result, for final analysis seven adjustment options were accepted, where the optimum one was chosen (adjustment to thirteen constant points, mean error of point's height ±0.5 mm, maximum error ±1.3 mm, mean error at the measuring position ±0.22 mm). Obtained accuracy characteristics show high precision of the measurement, comparable to the accuracy of 1^{st} and 2^{nd} class of state leveling. The accuracy of the determination of the reference points (from GPS measurement) are compatible to the accuracy of classical reference to the precision of a measurement itself, observation network can be regarded as integrated then.

7. Orientation of Mine Workings

To carry out the orientation three existing and two newly established points in the vicinity of shafts were used; their coordinates were determined during the measurement of the whole observation network of GPS points. Additionally, near the main shafts of the mine a 500 m long base for the observations of gyroazimuth was established; the co-ordinates of the ends of the base were also determined from GPS measurement. Based on GPS points the orientation of the mine was made. It involved 5 mine shafts and was done applying the method of de-plumbing of two mechanical plumbs, with Weisbach's reference, strengthened by the measurements of the gyroazimuths of the sides of reference triangle. The coordinates of the points and azimuths of traverse sides on each level of the mine were determined. Determined points were joint by traverse measurement, fortifying the obtained network with gyroscope observations of azimuths. A highly accurate network of mine points was obtained this way (mean location error did not exceed ±5 mm). A transfer of the height on mine levels was done with the help of shaft tape in the geodesic control to GPS points of the network. Mean height error on the levels of the mine was ±2÷4 mm.

8. Observation of Landslides

To determine the level of the activity of landslides on the southern slope of the Wieliczka Valley the measurement of the location of points of the fragment of a network (established in 1985 for the observation of landslide movements) was made. This network was measured in 1985 - 1987 with traditional methods, where the mean location error was ±15÷21 mm. Present measurement was referred to four points of the network, the coordinates of which were determined from satellite observations by a differentiation method bsed on the points of Wieliczka's resistance network with the application of satellite receivers Ashtech MD XII. Sessions lasting 60÷90 min. were applied, with the time of signal integration equaling 15 seconds. The accuracy of the determination of the coordinates of these points was – for flat coordinates below ±5 mm.

The analysis of the measurement results showed that despite unfavorable conditions of the observation (many obstacles in the terrain made it necessary to apply many indirect points and unfavorable configurations of traverse sides, big height differences between neighboring points, difficulties in observation related to vegetation) the accuracy of the determination of the location of a net point after adjustment, on average equal ±10 mm was achieved, so it was 1.5÷2.1 times more than in the case of previously used classical way of measurement. Mean error of the height of the point after the adjustment was ±0.5 mm (Maciaszek et alt., 1997)

Comparison of the determined flat and height coordinates with the coordinates of these points, defined in previous years by classical methods allowed to calculate horizontal and vertical dislocations.

9. Comparison of the Results of GPS Measurements by a Static Method and RTK for Two Types of Receivers (from Different Companies) and the Length Measurement with an Electronic Distance Meter

In the framework of the research an experiment was made. It was comparison of the results from GPS measurement by a static method (session time 0.5 hour) and kinematic method, as well as a classical measurement with an electronic distance meter. In a tested network of 40 points, located in the area of 0.5 x 0.5 km a measurement of points' coordinates was made by a SPECTRA receiver, using a static method (on 33 points) and kinematic method RTK (on 40 points) as well as kinematic method RTK with Leica receiver (on 35 points). These points were in the distance of 25÷50 m. Point coordinates were defined in a local system, regarding the reduction on a mean level of the area (according to the parameters of a local system). As the result of the analysis of the obtained results the occurrence of major errors of the location of the points determined by SPECTRA receivers was detected. They were particularly visible in short distances. For the definition of the dislocation of the coordinates, obtained with the help of both kinds of receivers, Helmert's transformation was used The occurrence of the deformation of scale was also detected. They were greater with SPECTRA receivers, increasing the system – opposite to the measurement with Leica, receivers – small decrease of the scale). Mean bias of the determination of the location compared to static method was 11÷13 mm for the SPECTRA receivers and 3÷5 mm for Leica receivers.

After the transformation between the systems of coordinates of the points, obtained from a static method and RTK method, according to the relationship:

$$v = a + bX + cY - (h^{STAT} - h^{RTK}) \tag{4}$$

where: a, b, c – coordinates,
X,Y – flat coordinates
h^{STAT}, h^{RTK} – heights from classical and RTK methods,
the possibility of height determination was obtained. Mean bias of the height obtained with SPECTRA receivers was 12 mm (maximum 32 mm), for Leica receivers it was 16 mm (maximum 43 mm).

10. Conclusions

1. Classical methods of the measurement of the surface deformation do not give satisfying results in terms of the accuracy of the value of parameters, especially horizontal dislocations. The cause of this are: small accuracy of the reference of observations to the existing canvas and the errors of this canvas. The use of contemporary measurement technologies (satellite measurements and precise electronic instruments) allows to create integral observation networks and the determination of deformation indexes with great accuracy (even by one order higher than in classical measurements).
2. Research done in the area of Wieliczka with the use of GPS technology indicate the possibility of the indication of the determination of the location of points and their horizontal dislocations with the mean error not exceeding ±3 mm, and also the height of the points and their subsidence with the mean error ±5 mm.
3. Mean error of the definition of horizontal dislocations of the points of the network, referred to GPS points and measured with the use of precise electronic instruments is up to ±10 mm (several times less than in classical measurements).
4. Errors of the definition of the situation of the points in the measurement by RTK method (with the use of SPECTRA and Wild-Leica receivers) do not exceed ±3 cm (on average errors range ±3÷13 mm), and the errors of the height determination - ±5 cm (on average errors range ±12÷16 mm). This enables the determination of surface subsidence (particularly in big and quickly following deformations) with the accuracy greater than with classical total station method.
5. Carried out experiments allow to state that the technology based on the measurements of GPS signals and the use of precise electronic instruments allows the integration of measurement methods used so far and the determination of the scale of deformations of the surface and rock mass with the accuracy exceeding classical methods several times. This technology can be used in examining deformations both in small as well as large areas (above 100 km^2).

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