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Evaluation of ground-based methods for monitoring neotectonic processes at geodynamic sites

Bohdan Lysko*

PhD in Technical Sciences, Lecturer
Ivano-Frankivsk National Technical University of Oil and Gas
76019, 15 Karpatska Str., Ivano-Frankivsk, Ukraine
https://orcid.org/0000-0002-2525-1557

Taras Hutsul

PhD in Technical Sciences, Associate Professor
Yuriy Fedkovych Chernivtsi National University
58012, 2 Kotsiubynskyi Str., Chernivtsi, Ukraine
https://orcid.org/0000-0002-7192-3289

Abstract. The relevance of the article lies in the need to improve the methods of monitoring neotectonic processes and develop technological parameters to ensure more effective forecasting of geodynamic phenomena. Accurate monitoring of neotectonic processes is important for assessing changes in geological conditions and preventing potential risks affecting the environment and human life safety. The purpose of research was to evaluate the effectiveness of various ground-based methods of monitoring neotectonic processes to determine their reliability and accuracy. The authors used different methods, in particular geodetic measurements, which ensure high accuracy and reliability of the results; geophysical methods that help to detect subsurface structures and processes; and remote sensing of the Earth, which provides large-scale monitoring and analysis of the dynamics of neotectonic phenomena. Having analysed the existing methods of determining the changes in the shape of the equipotential surface, the advantages of using geodetic measurements to ensure the accuracy and reliability of the measurement results were identified and substantiated. The proposed methodology is based on the study of changes in the shape of the equipotential surface on geotechnological sites and takes into account the inhomogeneity of the gravity field, and if the developed technological parameters are followed, it ensures the determination of the deflection of plumb lines with an accuracy of ± 0.2". The research results showed that the combination of these methods helps to obtain a more complex picture of neotectonic processes, which, in turn, contributes to more accurate forecasting and prevention of the consequences of geodynamic phenomena. The proposed approach to monitoring neotectonic processes can be used to develop effective strategies for monitoring and managing environmental risks associated with geological hazards

Keywords: hypsometric elevations; orthometric correction; geoid; deflection of the plumb line from the normal; geometric levelling; GNSS observation

Introduction

Earthquakes and other unfavourable underground physical and geographical processes, such as erosion, landslides, mudslides, karst, continue to pose a significant threat to human life and cause risks to the safe operation of buildings and structures on the Earth's surface. The main approaches and methods for solving the problem of monitoring neotectonic processes include the use of satellite data, geodetic measurements and numerical modelling. The disadvantages of existing approaches include high cost, complexity of integration of different data types, and insufficient accuracy

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*Corresponding author

in short-term forecasting. This indicates the need to develop new methods that take into account these limitations and provide more accurate and operational monitoring. Research and development in this direction will contribute to minimising the destructive impact of earthquakes and adverse physical-geographical processes on society, as well as deepen the existing understanding of the structure and dynamics of the Earth's surface movement.

According to D.R. Raban & A. Gordon (2020), the rapid progress of information technology has contributed to the exponential growth of big data volumes, including spatial data. Researchers M. Shafapourtehrany *et al.* (2023) also noted the development of forecasting and simulation modelling techniques, but short-term earthquake forecasting remains a challenging and unsolved problem. According to M. Pakshyn *et al.* (2019), satellite technologies such as synthetic aperture interferometry allow obtaining high-precision data on changes in the Earth's surface. However, these methods have their limitations in the form of high cost and the need for specialised equipment. Among the available technologies for earthquake research, remote sensing is widely used due to its unique characteristics such as rapid image acquisition and wide image acquisition range. However, early studies of pre-earthquake anomalies and remote sensing are mostly focused on anomaly identification and analysis of a single physical parameter. The combination by researchers P. Xiong *et al.* (2021) of infrared and hyperspectral studies of the terrain over a significant period of time is quite voluminous, and cannot do without the participation of machine learning methods, the results of which demonstrate a strong ability to improve earthquake forecasting.

X. Zhao *et al.* (2021) tentatively distinguished four application areas of remote sensing data for earthquake prediction based on observed anomalies: thermal anomalies, electromagnetic signal anomalies, crustal deformations, and gravity anomalies. C. Geiß *et al.* (2020) noted that geodetic methods, particularly ground-based global navigation satellite systems (GNSS), are effective for monitoring deformation, but their accuracy depends on the density of the observing stations network. C. Chen *et al.* (2020) considered it possible to track surface displacements with GNSS data that exhibit elastic deformation and/or oscillations in the spatiotemporal domain, if double-amplitude vibrations actually exist. Vertical displacements obtained from ground-based GNSS receivers can be taken into account to test the effects of double-amplitude vibrations in dynamic range seismic records at such low frequencies (i.e., a cycle of about 2 hours).

The main approaches and techniques used to monitor neotectonic processes include synthetic aperture radar (InSAR) interferometry, GNSS, and gravity variation analysis. According to J.B. Rundle *et al.* (2021), InSAR allows obtaining high-precision images of deformations of the Earth's surface. However, according to researchers S. Nandan *et al.* (2021), this method has limitations in densely built-up or forested areas due to the possibility of signal loss. M. Bagheri-Gavkosh *et al.* (2021) emphasised the importance of integrating different methods to ensure a comprehensive approach to monitoring. The researchers highlighted the importance of monitoring changes and deformations of the Earth's surface to understand the impact of anthropogenic activities, which currently pose major challenges to the global community. O. Lavryk (2018) stated that the monitoring of landscapes and technical systems is part of interdisciplinary geotechnical monitoring, which is carried out for the comprehensive study of changes in the Earth's surface and their dynamics, as well as for the study of factors affecting displacement.

Despite significant progress in monitoring technologies, existing approaches have limitations. Some techniques, such as InSAR, may be limited by terrain conditions. GNSS-based methods require significant financial and technical resources for installation and maintenance. Therefore, there is a need to develop new techniques that can provide accuracy and reliability at lower costs and less dependence on local conditions. The purpose of this work was to develop a methodology and substantiation of technological parameters to study changes in the shape of the equipotential surface on geotechnological sites. The scientific novelty of the research lies in the fact that new approaches to monitoring neotectonic processes have been developed, which take into account modern technological capabilities and ensure high accuracy and speed of data. The technological parameters used to study changes in the shape of the equipotential surface on geotechnological polygons have been investigated, which ensures the accuracy of determining the deflection of plumb lines of 0.2" and takes into account the inhomogeneity of the gravity field.

Materials and Methods

Investigating the influence of the level surface shape on the results of geodetic levelling, P. Dvulit *et al.* (2012) stated that in mountainous areas, the mean square error of the deflection of the plumb line from the normal is 8", and the maximum value can reach 1". Regardless of the complexity of the topography and terrain anomalies, the deflection of vertical components can be calculated with an accuracy of more than 0.1" using the provided formulas. In (1), the accuracy of calculating the deflections of plumb lines from the normals expressed in terms of the root mean square error is calculated:

$$m_\varepsilon = \frac{\rho}{S \sin Z} \times m_h, \tag{1}$$

where m_ε is the accuracy of calculating deflections of plumb lines from normals; m_h is the root mean square error to determine elevations; S is the distance between site points; Z is zenith distance; ρ is a constant describing the number of seconds in one radian (206,265"). The mean square error of geometric levelling for Class I is calculated by the formula:

$$m_h^2 = \eta^2 \times S + \sigma^2 \times S^2, \tag{2}$$

where η is the random error of geometric levelling (0.8 mm is taken for Class I); σ is the systematic error of geometric levelling (0.08 mm is taken for Class I) according to (Perii, 2019); S is the distance between site points. The deflection of the plumb line from the normal is determined by comparing the zenith distances obtained with the help of GNSS levelling Z^{GNSS} (determined in relation to the ellipsoid) and geometric levelling Z^{ort} (determined in relation to the geoid):

$$\varepsilon = Z^{GNSS} - Z^{ort}, \tag{3}$$

where ε is the deflection of the plumb line from the normal. Figure 1 shows a section along a vertical plane between two points of a geodynamic site with a given azimuth – α_{AB}. Thus, in Figure 1, plumb lines and the normal are represented as projections on a vertical section, which is a plane of a direct normal section. This section includes the normals to the ellipsoid at points A and B, as well as the projected normal that is goes down from point B to point A.

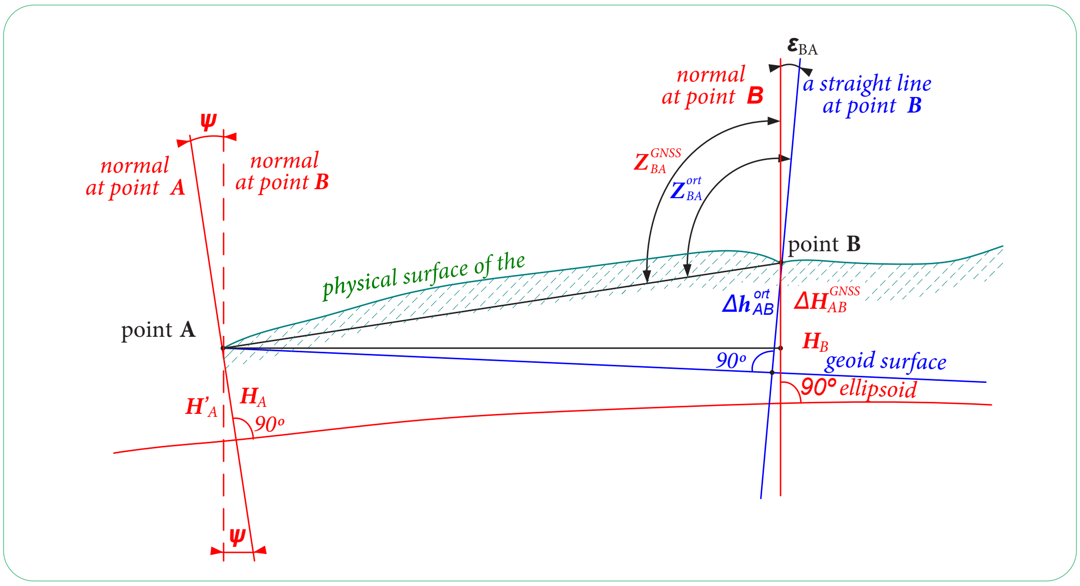

Figure 1. Vertical section along the line of the geodynamic site

Source: created by the authors

To calculate the zenith distances of Z^{GNSS} and Z^{ort}, it is necessary to determine the height difference of two points relative to the surface of the geoid and the reference ellipsoid, and their geodetic coordinates (Lysko, 2023). Based on Figure 1, the following was obtained:

$$Z_{AB}^{GNSS} = arccos\frac{\Delta H_{AB}^{GNSS}}{S_{AB}};$$
$$Z_{BA}^{GNSS} = 180 - arccos\frac{\Delta H_{BA}^{GNSS}}{S_{AB}};$$
$$Z_{AB}^{ort} = arccos\frac{\Delta h_{AB}^{ort}}{S_{AB}};$$
$$Z_{BA}^{ort} = 180 - arccos\frac{\Delta h_{BA}^{ort}}{S_{AB}}, \tag{4}$$

where ΔH_{AB}^{GNSS} is the difference in geodesic heights with account of the normal projection; Δh_{AB}^{ort} – is the difference in hypsometric heights with account of the orthometric correction; S is the distance between polygon sites. As the normals at points B and A were not parallel to each other, a projection of the normal was made, which was taken from point B to point A. Thus, the following formula was used to determine the elevations by geodetic heights of the points:

$$H_{AB}^{GNSS} = H_B - \frac{H_A}{sin\,\psi}, \tag{5}$$

where ΔH_{AB}^{GNSS} is the difference in geodesic heights with account of the normal projection, taken from point B to point A; ψ is a dihedral angle formed by two normal, which is calculated according to the formula from analytical geometry, as an angle between two vectors. Hypsometric elevations dh^{ort} describe the physical surface of the Earth relative to the horizontal. This is the more difficult part to determine compared to geodesic elevations. Hypsometric elevations were obtained according to the formula:

$$\Delta h_{AB}^{ort} = [h]_{AB} + 0_{AB}^{ort}, \tag{6}$$

where $[h]_{OP}$ is the sum of elevations between observation stations O and P, obtained from geometric levelling data and corrected by orthometric p^{ort} correction. In the S. Perii (2019) study, to determine the zenith distances Z^{GNSS} and Z^{ort} the equations of the normals are solved, which go down from the observation stations A and B. Given the parameters of the ellipsoid (WGS84), the coordinates of the intersection of the normals with the Z axis at the points nA and nB were found. The coordinates of the intersection points of the normals with the Z axis were determined by calculating the distances $0nA$ and $0nB$ from the origin of the coordinates to the intersection points. Since the coordinates of the observation points are obtained from GNSS measurements, the coordinates of the intersection points with the Z axis are obtained by formulas using the parameters of the reference ellipsoid (Zakatov, 1962).

$$\left.\begin{array}{l} X_{nA}=Y_{nA}=0 \\ Z_{nA}=-\frac{ae^2 \sin B_A}{\sqrt{1-e^2 \sin^2 B_A}} \end{array}\right\}; \quad \left.\begin{array}{l} X_{nB}=Y_{nB}=0 \\ Z_{nB}=-\frac{ae^2 \sin B_B}{\sqrt{1-e^2 \sin^2 B_B}} \end{array}\right\}, \tag{7}$$

where $e \rightleftarrows a$ are the geometric parameters of the referent ellipsoid; B is the geodetic latitude of the point. The coordinates of points nA and nB on the Z axis acquired the values $(0, 0, Z_A)$ $(0, 0, Z_B)$, respectively. Zenith distances are calculated as the angle between two vectors using the geocentric coordinates of points:

$$\begin{aligned} Z_{AB}^{GNSS} &= arccos(\frac{X_A(X_B-X_A)+Y_A(Y_B-Y_A)+(Z_A-Z_{nA})(Z_B-Z_A)}{\sqrt{X_A^2+Y_A^2+(Z_A-Z_{nA})^2}\times\sqrt{(X_B-X_A)^2+(Y_B-Y_A)^2+(Z_B-Z_A)^2}}; \\ Z_{BA}^{GNSS} &= arccos(\frac{X_B(X_A-X_B)+Y_B(Y_A-Y_B)+(Z_B-Z_{nB})(Z_A-Z_B)}{\sqrt{X_B^2+Y_B^2+(Z_B-Z_{nB})^2}\times\sqrt{(X_A-X_B)^2+(Y_A-Y_B)^2+(Z_A-Z_B)^2}}. \end{aligned} \tag{8}$$

Although these methods are conceptually different, they rely on the results of geometric levelling together with data on the vertical gradient of gravity to determine the hypsometric component dh^{ort} (orthometric height of a physical point on the Earth above the geoid) and high-precision GNSS measurements. To ensure the maximum level of accuracy and reliability of the obtained results, when developing an alternative method of determining deflections of plumb lines, the following condition should be observed: heights have to be determined unambiguously, regardless of the levelling method. To strictly comply with this requirement, it is necessary to use the geopotential value $C=\int_O^P gdh$. This integral does not depend on the form or path of integration, that is, integration along different levelling courses should give the same result; the heights should be determined based only on the results of direct measurements on the physical surface of the Earth, without using hypothetical data about its internal structure. Hypothetical data are subject to interpretation and internal assumptions, which may adversely affect the objectivity of the results; the accepted system of heights should correspond to a rather strict method of determining the geoidal component of a geometric or geodetic height. The optimal solution for height provision of a geodynamic site is using the orthometric system of heights and developing a direct connection with geodetic heights. This possibility is provided by Helmert's differential formula for determining the elevations of the geoid:

$$d\zeta = \zeta_O - \zeta_P = -\int_A^B \varepsilon^e dl - \int_A^B \frac{g-\gamma}{\gamma} dh, \tag{9}$$

where ε^e is the mean value of the plumb line deflections determined on the physical surface of the Earth; l is the distance between observation stations. Since the geoid is a level surface and any hypsometric elevations of dh on this surface will be zero, then equation (9) has taken the following form:

$$d\zeta = \zeta_O - \zeta_P = -\int_A^B \varepsilon^e dl. \tag{10}$$

Based on equation (10), the deflection of the plumb line was expressed in the following way:

$$\varepsilon^e = \frac{d\zeta}{dl}. \tag{11}$$

The heights difference of the geoid $d\zeta$ cannot be obtained from the results of direct measurements on the physical surface of the Earth, and the use of hypothetical data about its internal structure is subject to interpretation and internal assumptions. It is appropriate to express the difference in geoid heights $d\zeta$ through geodesic ΔH_{OP}^{geod} and orthometric dh^{ort} heights. This possibility is directly provided by the integral formula of the generalised astronomical levelling. It is provided in the following interpretation:

$$d\zeta = \int_O^P dH^{geod} - \int_O^P dh^{ort}. \tag{12}$$

This approach made it possible to additionally control the results of measurements due to the comparison of geodetic elevations obtained directly from GNSS measurements and from the results of ground-based measurements, which provides a significant advantage of using the proposed technique in comparison with existing analogues.

Results

A number of various factors, such as tectonic activity, subsidence due to withdrawal of liquids from the subsurface, and volcanic activity, cause deformations of the Earth's surface. These processes lead to a redistribution of masses in the Earth's crust, a change in the gravitational potential, and therefore a change in the shape of the equipotential surface. Measuring the change in the shape of the equipotential surface helps to get an idea of the main geological processes and gravitational potentials. Observing the nature of these changes provides insight into the nature and degree of deformation of the Earth's surface and is the basis for short-term forecasting. Deformation, in the broadest sense, is a change in shape and dimensions. As the form and figure are related to the metric characteristics of bodies, deformation, in a broad sense, is also related to the change in such characteristics of general physical or even abstract entities. It is only necessary for the elements of such objects to be brought into correspondence with each other, just as through the identification of material points a correspondence is established between two different states of a deformable body. Studying the dimensions, shape and gravitational field of the Earth, determining the position, changes in time of all of the above mentioned, as well as their representation, play an important role in investigating the processes taking place on the planet (Dermanis & Livieratos, 2023). This issue is particularly relevant for environmental safety, since by monitoring neotectonic processes it is possible to predict their course for the timely warning of society in order to minimise probable destructive consequences.

Significant negative consequences of surface deformations have led to the existence of numerous methods of studying and monitoring deformations of the Earth's surface, which arise as a result of natural geodynamic processes, man-made and exogenous factors. The choice of measuring devices and methods or the creation of a special monitoring system depends on different types of deformations, which will affect the stability analysis method and, accordingly, the entire deformation monitoring system. The study of spatio-temporal deformation changes of technogenically destabilised territories includes a number of geodetic, geological, geophysical, geotechnical methods or their combinations. Geodetic methods can be divided into remote, terrestrial and terrestrial-remote based on the spatial location of research instruments at the time of shooting. The main directions of the development of modern geodesy are related to the development of information technologies, in particular, GNSS, high-resolution orbital systems for creating surface deformation maps or a digital terrain model (Karpinsky & Lazorenko-Hevel, 2018).

The development of powerful means of obtaining spatial information about the Earth is based on a variety of technologies, including optical-electronic terrain scanning systems, satellite radar, laser location on ground and air platforms, digital aerial photography (including the use of unmanned aerial vehicles (UAV) and non-metric cameras), pictographic imaging to create realistic terrain models, digital methods of processing images and geospatial information, and extensive use of GIS and telecommunications technologies to provide public access to geospatial data. V. Hlotov & M. Biala (2023) proposed a detailed classification of current geodetic methods and techniques of researching quantitative parameters of deformation processes of subsidence-settlement of the Earth's surface of man-made destabilised territories (Fig. 2).

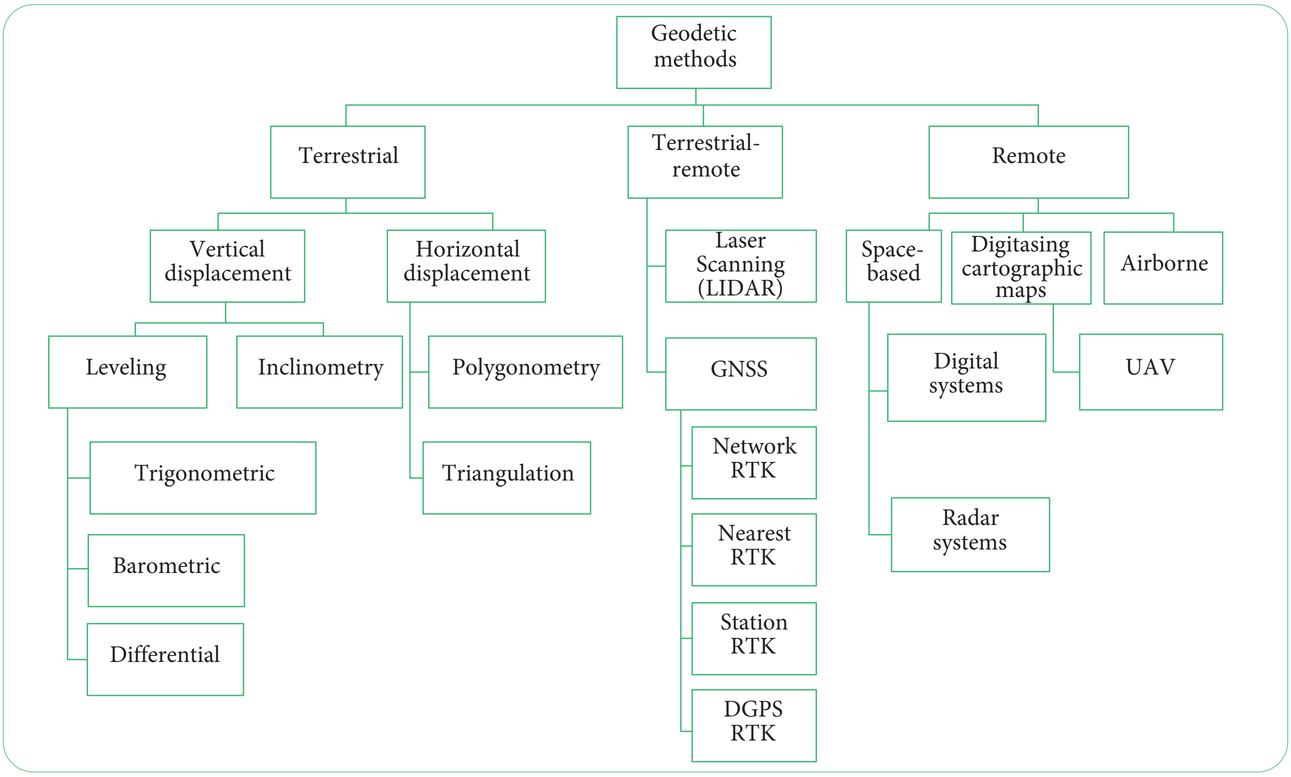

Figure 2. Classification of relevant geodetic methods for monitoring and studying deformation spatio-temporal changes of the Earth's surface in man-made destabilised territories
Note: RTK – real time kinematic; DGPS – differential global positioning system
Source: created by the authors based on V. Hlotov & M. Biala (2023)

The collected data are used to protect the natural environment through the identification and monitoring of areas with an increased risk of natural disasters, which allows timely preventive measures. To ensure environmental safety and the safety of human life in the studied territories, the data are used to predict and minimise risks associated with earthquakes and other adverse physical and geographic processes. This facilitates the development of effective evacuation plans and emergency response measures. The rational use of natural resources is ensured through the assessment of their state and the dynamics of changes, which allows planning their sustainable use. In the programs of regional development of territories, the data helps to determine the safest and most stable areas for construction and infrastructure development, taking into account possible geological threats (Zayats *et al.*, 2017).

Remote sensing methods based on the analysis of the Earth's gravity field are widely used to determine changes in the equipotential surface. These methods include satellite gravimetry, doppler interferometry, satellite altimetry and satellite laser ranging. Methods based on the use of InSAR deserve special attention among the above measurement methods. InSAR results are partially available for public use and have become widely used in scientific research. Their main advantage is the possibility of carrying out mapping and monitoring of the Earth's surface deformation on a continental scale (Kalia *et al.*, 2017; Raspini *et al.*, 2018). Data obtained from orbital satellites help to get global data about the Earth's gravitational field, which can potentially be used to monitor changes in the equipotential surface.

Methods that are carried out on the Earth's surface consist in measuring the deflection of a plumb line or the change in the strength of the Earth's gravitational field directly on the ground. They can provide higher accuracy compared to remote methods, optimal resolution, they have advantages in ease of maintenance and independence from weather conditions. Such advantages of terrestrial methods in determining changes in the equipotential surface make them more reliable and suitable for predicting deformations of the Earth's surface. These methods make it possible to detect local changes in the equipotential surface, which is an additional advantage in their application. Gravimeters are widely used to measure the strength of the gravitational field on the Earth's surface. Maps of the Earth's gravitational field can be developed based on the dynamics of changes in the gravitational field intensity over time. These maps are used to determine changes in the shape of the equipotential surface. These data allow for high accuracy and are used to monitor changes in the Earth's gravitational field, both local and regional (Burak, 2022).

When using ground-based gravity methods, there is no influence of atmospheric interference and positioning errors. However, the disadvantage of these measurements is the low efficiency, since one point can take several tens of hours to measure. Ground-based gravimetric measurements respond to local terrain characteristics because they are performed on the physical surface of the Earth, not on the geoid itself. If changes in the distribution of topographic masses occur above the geoid surface, this will not affect the geoid shape, as such masses are not taken into account when determining it. However, changes in mass distribution can still lead to deflections in the gravitational potential on the Earth's surface. Ground-based gravimetry methods, such as relative and absolute gravimetry, provide a direct measurement of the gravitational potential, making them particularly sensitive to changes in the mass distribution over the geoid surface. Nevertheless, they can be effective in detecting changes in the geoid shape if combined with high-precision geodetic measurements.

P. Dvulit *et al.* (2019) singled out methods that are not affected by the change in mass distribution over the geoid surface as particularly promising for determining the deflection of plumb line. Such methods include astro-geodetic levelling, geometric levelling, and GNSS levelling, which focus on determining the direction or vector of gravity, instead of the absolute value of the gravitational potential (Ceylan, 2009). Changes in the direction of gravity help to make inferences about changes in mass distribution that affect the gravitational field, without the need to consider the absolute value of the gravitational potential. This approach was taken into account during the development of the proposed methodology, which made it possible to obtain a more comprehensive picture during the monitoring of neotectonic processes.

Based on the calculations, differential equations were obtained and the influence of technological parameters on the accuracy of determining the deflection of plumb lines from normals was investigated, depending on the chosen method. Geodetic and hypsometric elevations are considered to be uncorrelated, so the root mean square error of the function can be obtained by summing the squares of the partial derivatives calculated for each variable. When using the technique based on the comparison of zenith distances obtained with the help of hypsometric and geodetic heights (hereinafter Method I), the generalised differential equation look as follows:

$$\sigma_{\varepsilon}^2 = \left(\frac{1}{S_{AB}^2 - \Delta H_{AB}^2}\right)(\sigma_{\Delta H}^2 + \sigma_{\Delta h}^2) + 2\left(\frac{\Delta H_{AB}^2}{S_{AB}^2(S_{AB}^2 - \Delta H_{AB}^2)}\right)\sigma_{\Delta S}^2, \quad (13)$$

where $\sigma_{\Delta H}^2$ is the accuracy of determining the difference in geodetic heights; $\sigma_{\Delta h}^2$ is the accuracy of determining hypsometric elevations; $\sigma_{\Delta S}^2$ is the accuracy of determining the distance between observation stations; S is the distance between site points. The differential equation of the proposed method of determining deflections of plumb lines, based on Helmert formula for astronomical levelling (hereinafter Method II) look as follows:

$$\sigma_{\varepsilon}^2 = \frac{1}{S_{AB}^2}(\sigma_{\Delta H}^2 + \sigma_{\Delta h}^2) + \left(\frac{\Delta H_{AB}^{GNSS} - \Delta h_{AB}^{ort}}{S_{AB}^2}\right)^2 \sigma_{\Delta S}^2. \quad (14)$$

Based on the analysis of differential equations (13-14), it can be concluded that the obtained accuracy of determining the deflection of a plumb line from the normal (σ_{ε}^2) depends on the squares of the measurement errors of hypsometric $\sigma_{\Delta h}^2$ and geodetic elevations $\sigma_{\Delta H}^2$ in direct proportion, and is inversely proportional to the square of the distance between the points S_{AB}^2. To study the influence of technological parameters on the accuracy of determining the deflection of plumb lines, response graphs (Fig. 3-5) were constructed depending on the variable factor (other factors were at a constant basic level).

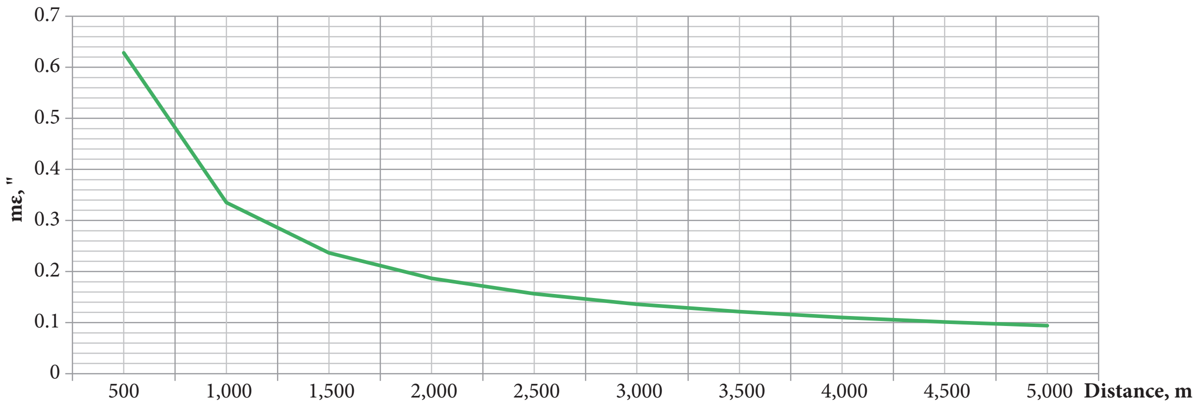

Figure 3. Calculation of the mean square error of determining the deflections of plumb lines depending on the distance between the site points for Method I

Note: the accuracy of determining geodetic elevations is 2 mm; the accuracy of orthometric elevations was calculated according to equation (2) taking into account the change in distance

Source: created by the authors

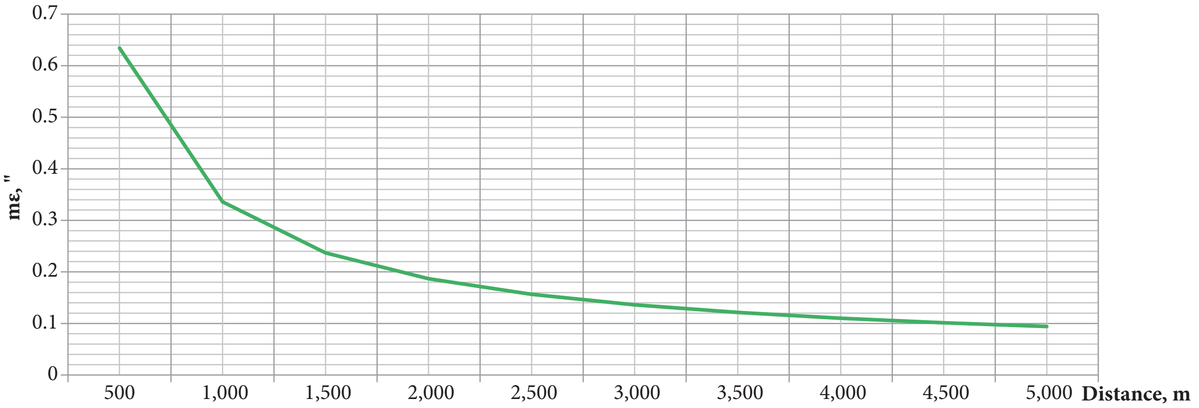

Figure 4. Calculation of the mean square error of determining the deflections of plumb lines depending on the distance between the site points for Method II

Note: the value of elevations between points is constant and is 50 m; the accuracy of determining geodetic elevations is 2 mm; the accuracy of orthometric elevations was calculated according to formula (2) taking into account the change in distance

Source: created by the authors

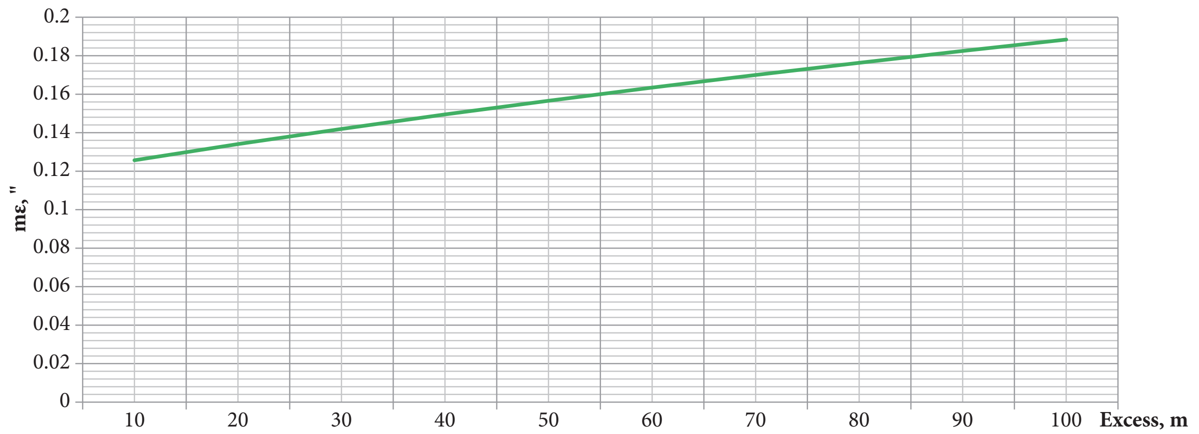

Figure 5. Calculation of the mean square error of determining the deflections of plumb lines depending on the elevations between site points for Method II

Note: the distance between the points is constant and is 2,500 m

Source: created by the authors

If with the help of precision levelling with a short beam $m_h = 0.5$ mm is reached, then already at distances from $S = 1$ km the deflection value of the plumb line from the normal will theoretically be $m_\varepsilon = 0.1$". Visually comparing the graphs shown in Figure 3 and Figure 4, a significant similarity can be observed. Further correlation analysis of the arrays of data that led to such a result made it possible to obtain an indicator of 0.999998, which indicates a very high direct connection between the two investigated methods according to the Chaddock scale. Thus, each of the methods can be used in the practical field, and the results obtained by them will satisfy the existing limit requirements for accuracy. According to the Figure 5, it can be stated that the accuracy of Method II is also influenced by the height difference between the site points. This factor should be taken into account when building geodynamic sites in foothills and mountainous areas, where significant differences in altitude are possible. The proposed methods can be used for altitudinal support, namely the observation of neotectonic processes at geodynamic and man-made polygons, and the determination of land surface subsidence at mining observation stations located under residential areas or in the immediate vicinity of them, as they can ensure the relative accuracy of the results of 1×10^{-6} and higher and take into account the inhomogeneities of the gravity field.

Discussion

In this work, research was carried out on the methods of determining the deflections of the plumb line from the normal and the methods of monitoring deformations of the Earth's surface, in particular in man-made destabilised territories. The results demonstrate the possibility of achieving high accuracy in determining these parameters, which is important for geodynamic research and ensuring environmental safety. Geodetic methods such as GNSS, InSAR, satellite gravimetry and laser location are becoming the main tools for monitoring the deformations of the Earth's surface. Iu. Karpinsky & N. Lazorenko-Hevel (2018) emphasised the importance of using modern technologies, such as the high-resolution orbital system, to produce accurate deformation maps and digital terrain models. They noted that the use of GNSS and InSAR allows obtaining global data on the Earth's gravity field and changes in the equipotential surface. The current study supports these findings by demonstrating high accuracy in determining plumb line deflections using GNSS and geometric levelling. At the same time, it has been established that the accuracy of the obtained data depends on the distance between the site points and the accuracy of determining geodetic elevations, which coincides with the conclusions of P. Dvulit *et al.* (2019).

The results obtained by V. Hlotov & M. Biala (2023) have shown the significant effectiveness of combined geodetic methods in monitoring deformation processes, in particular in man-made destabilised territories. They noted that the use of various methods, such as laser scanning and gravimetry, allows obtaining a more complete picture of the deformation processes. This study confirms these results, especially in the context of the application of astro-geodetic levelling and GNSS to determine deflections of plumb lines. Attention is drawn to the importance of taking into account orthometric corrections in calculations, which is confirmed by the authors' calculations of the mean square error. The use of InSAR to monitor deformations of the Earth's surface has become an important component of modern geodetic research. Studies conducted by F. Raspini *et al.* (2018) have shown that InSAR can provide accurate measurements of continental-scale deformations, which is important for global monitoring of changes in the Earth's gravity field. The study also confirmed the effectiveness of InSAR in the context of deformation monitoring, especially in combination with other methods such as terrestrial gravimetry and GNSS. The use of InSAR can be particularly useful in cases where it is necessary to provide monitoring over large areas with high resolution. Differential equations have been developed to estimate errors in determining the deflections of plumb lines from the normal depending on various technological parameters. This helps to accurately assess the impact of the distance between site points and the accuracy of determining the elevations on the overall accuracy of the results.

The deflection of plumb lines is an important area of research, as it is directly related to the shape of the equipotential surface (geoid). The geoid is characterised by the same gravitational potential at all its points, and the direction of gravity is perpendicular to this surface. This affects the deflection of plumb lines, and therefore, by measuring them in different places, one can get valuable information about the shape of the geoid. This approach makes it possible to study the nature of the deformation of the Earth's surface and the dynamics of movement in general. The deflection of plumb lines from normals is a component of determining geoidal heights based on the results of high-precision levelling. This is due to the heterogeneity of the topographic masses and the influence of other factors, such as the local topography, anomalies on the terrain, parameters and position of the ellipsoid. Other studies, such as the work of G. Herrera-García *et al.* (2021) also proved the importance of taking into account topographic and gravity anomalies in the process of determining the deflections of plumb lines. They emphasised that these factors can significantly affect the accuracy of determining geoid heights, especially in regions with complex topography or anomalous geological conditions.

The most effective methods for determining geodetic heights are approaches based on the use of GNSS. Due to the significant development of GNSS technologies, it became possible to determine the deflection of plumb lines with an accuracy of 0.1-0.2" and changes in the shape of equipotential surfaces with mm accuracy. The difference in geodetic heights ΔH_{OP}^{geod} with the help of GNSS levelling can be determined with an accuracy of ± 2 mm in the post-processing mode of measurements, which corresponds to the development of the Astrogeodetic Network of Ukraine of Class I. The achievement of this accuracy was possible thanks to the differential processing of the received data by the GAMIT/GLOBK method. Processing of the GNSS data include the use of precise satellite orbits, Earth orientation parameters, receiver clock and satellite clock corrections, and absolute phase centre variation models for receivers and satellite antennas. To accurately determine the shape of the equipotential surface, it is important to take into account the local topography, as well as to perform data processing using precise satellite orbits and Earth orientation parameters, as indicated in the research of H. Yuan *et al.* (2022). This makes it possible to obtain highly accurate results that reflect the real deformations of the Earth's surface and the dynamics of movement. The study has also developed technological parameters for obtaining optimal measurement results, namely: the distance between site points $S \geq 2$ km, the accuracy of determining geodetic elevations $\Delta H_{AB}^{GNSS} \leq 2$ mm, taking into account orthometric corrections and laying geometric levelling not lower than the Class I of accuracy. Given that the obtained data should be used to predict and minimise the risks associated with earthquakes and other adverse physical-geographical processes, which is directly related to the safety and livelihood of people, the developed technique provides an opportunity for additional control and evaluation of the results, which is a key advantage.

Researchers D.D. Basil *et al.* (2021) focused on the determination of deflection of vertical components using the integration of a global positioning system in the results of high-precision geometric levelling on the studied site. The obtained results were compared with the use of gravimetric models (EGM2008, EGM1996, EGM1984). Despite the obtained high results, the authors did not take into account the possible presence of anomalies on the territory of the site, or the heterogeneity of the Earth's masses, assuming that orthometric elevations will be equal to the results of geometric levelling. A comparative analysis of modern models of plumb line deflection has demonstrated that, despite the high overall accuracy of parameter determination, some models may have significant errors in individual regions. The data analysis has showed that the accuracy of models can vary depending on the regional features of the geoid and gravity field. For example, in regions with a complex geodetic profile or with significant local anomalies of the gravity field, the accuracy of the models may decrease. This is due to the fact that global models do not always take into account all local geodetic and gravity features. The studies by H. Yuan *et al.* (2022) proved that the EGM2008 model showed slightly higher accuracy in some regions compared to EIGEN-6C4, especially in regions with intense geodynamic processes. However, EIGEN-6C4 proved to be more accurate in regions with lower gravity variability. This indicates that the choice of model for specific geodetic problems should be based on the characteristics of the region where the measurements are made. Thus, modern geoid models such as EGM2008 and EIGEN-6C4 demonstrate high overall accuracy, but their performance may vary depending on regional features. To ensure the highest accuracy in specific regions, it is recommended to perform local corrections and analysis of data obtained using ground-based methods for determining the deflection of a plumb line.

G. Herrera-García *et al.* (2021) noted that the use of GNSS for monitoring neotectonic processes allows obtaining accurate data on the displacement of the Earth's surface in real time. However, this method requires the installation of stationary stations, which can be expensive and technically difficult in remote areas. The scientists also state, as it is shown in their study, that the primary task in investigating neotectonic processes is to create a network of regional geodynamic sites and develop methods that allow determining the deflection of a plumb line from the normal with an accuracy of ± 0.2" or a change in the shape of the geoid with an accuracy of up to 5 mm (Procedure for Building the State Geodetic Network, 2013). This approach has not been implemented in previous studies and is an important contribution to the field of geodesy and deformation monitoring. Thus, current article proposed a methodology and substantiates the technological parameters that can be used for studies of changes in the shape of the equipotential surface on geotechnological sites, ensuring the accuracy of determining the deflection of plumb lines of 0.2" and taking into account the inhomogeneity of the gravitational field. It is proved that methods of ground gravimetry, such as relative and absolute gravimetry, can be effective for determining local changes in the Earth's gravity field. The results confirm and extend previous studies in the field of Earth surface deformations.

Conclusions

The study of determining the deflections of plumb lines and their influence on ground geodetic measurements has led to the following results. A comparative analysis of plumb line deflection models has showed that modern models provide high accuracy in determining parameters, but may have significant errors in certain regions. An improved method of determining plumb lines deflections has been developed based on the use of GNSS observations and data on the vertical component of the gravity potential at reference points. This technique makes it possible to increase the accuracy of determining the deviation of the vertical line, reducing the impact of systematic errors associated with not taking into account the hypsometric component during measurements. A significant advantage of the proposed methodology is the ability to control measurement results due to the comparison of geodetic elevations obtained directly from GNSS measurements and from the results of ground measurements.

The technological parameters for the construction of geodynamic sites and the improvement of precision measurements carried out on them have been developed. The implementation of these recommendations helps to increase the efficiency and accuracy of work, reducing the time and resources spent on adjusting measurement results. Detailed calculation formulas (13) and (14) have been developed to assess the accuracy of determining the deflection of plumb lines. These formulas take into account the accuracy of the difference in geodetic heights obtained from precise GPS measurements. They also take into account hypsometric elevations, which are defined as the difference in height between two points, taking into account corrections for the curvature of the Earth's surface and other geodetic factors. In addition, the formulas take into account the distances between the observation stations, since a larger distance between the stations can increase the influence of local anomalies of the gravity field. All these components are taken into account not only in terms of their accuracy, but also their actual values, which makes it possible to achieve high accuracy when determining the deflection of plumb lines. The proposed Method I and Method II can be used to study changes in the shape of the equipotential surface on geotechnological sites, as they ensure the accuracy of determining the deflection of plumb lines of 0.2" and take into account the inhomogeneity of the gravitational field while observing the obtained technological parameters. In future research, it is worth focusing on the approbation of the developed methods on the network of observation stations of the Kalush-Holyn Deposit and the impact study of the gravity field inhomogeneity on the height determination accuracy in the area with a non-homogeneous gravity field.

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Conflict of Interest

None.

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Оцінка наземних методів моніторингу неотектонічних процесів на геодинамічних полігонах

Богдан Лиско

Кандидат технічних наук, викладач
Івано-Франківський національний технічний університет нафти і газу
76019, вул. Карпатська, 15, м. Івано-Франківськ, Україна
https://orcid.org/0000-0002-2525-1557

Тарас Гуцул

Кандидат технічних наук, доцент
Чернівецький національний університет імені Юрія Федьковича
58012, вул. Коцюбинського, 2, м. Чернівці, Україна
https://orcid.org/0000-0002-7192-3289

Анотація. Актуальність роботи полягає у необхідності вдосконалення методів моніторингу неотектонічних процесів та розробленні технологічних параметрів для забезпечення більш ефективного прогнозування геодинамічних явищ. Точний моніторинг неотектонічних процесів є важливим для оцінки змін геологічних умов та попередження потенційних ризиків, що впливають на екологічну безпеку та безпеку життєдіяльності людини. Метою дослідження була оцінка ефективності різних наземних методів моніторингу неотектонічних процесів для визначення їхньої надійності та точності. У дослідженні використано методи, зокрема геодезичні вимірювання, які забезпечують високу точність та достовірність результатів; геофізичні методи, що дозволяють виявити підповерхневі структури та процеси; а також дистанційне зондування Землі, яке забезпечує широкомасштабний моніторинг та аналіз динаміки неотектонічних явищ. Проаналізувавши існуючі методи визначення зміни форми еквіпотенціальної поверхні, виявлено та обґрунтовано переваги використання геодезичних вимірювань для забезпечення точності та достовірності результатів вимірювань. Запропонована методика ґрунтується на дослідженні зміни форм еквіпотенціальної поверхні на геотехногенних полігонах та враховує неоднорідність гравітаційного поля, а при дотриманні розроблених технологічних параметрів забезпечує визначення відхилення прямовисних ліній із точністю ± 0,2". Результати дослідження показали, що комбінування цих методів дозволяє отримати більш комплексну картину неотектонічних процесів, що також сприяє більш точному прогнозуванню та запобіганню наслідків геодинамічних явищ. Запропонований підхід до моніторингу неотектонічних процесів може бути використаний для розробки ефективних стратегій моніторингу та управління екологічними ризиками, пов'язаних із геологічними небезпеками

Ключові слова: гіпсометричні перевищення; ортометрична поправка; геоїд; відхилення прямовисної лінії від нормалі; геометричне нівелювання; GNSS-спостереження