ISSN 2029-6991 / eISSN 2029-7009

GEODESY and CARTOGRAPHY

2025
Volume 51
Issue 2
Pages 50–60
https://doi.org/10.3846/gac.2025.20300

UDC 528.481

GEODETIC MONITORING OF LANDSLIDE PROCESSES IN COASTAL TERRITORIES

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Article History:
- received 02 November 2023
- accepted 04 March 2025

Abstract. The study is devoted to the methodology and features of geodetic monitoring of territories to provide analytical and predictive information regarding predicting the danger of coastal strip landslide processes. The causes, consequences, and risks of the development of landslide processes are analysed. The purpose of the study was to justify the need and to consider the methodology of stable high-precision observations of the coastal fortification structure, to identify the zone of active landslides, and to provide suggestions regarding the features and conditions of further observations. To conduct direct observations, it was necessary to lay benchmarks on the territory of the research object. The method using GNSS technologies was chosen for determining the coordinates of benchmarks at the research object. The advantages of using GNSS equipment for monitoring slope deformations compared to traditional geodetic methods have been determined. To achieve the maximum accuracy of measurements, it was decided to install a constantly operating satellite station of the "System.NET" network directly in the work area. During the study period, 33 geodetic soil benchmarks and 53 benchmarks were installed on the coastal fortification structure in the coastal zone. In combination with the methods of geodetic observations, such a density and distribution of benchmarks both in the soil and on the coastal fortification structure made it possible to obtain accurate data on the dynamics of landslide processes and to prevent the negative consequences of the landslide.

Keywords: geodetic monitoring, GNSS observations, landslide processes, coastal strip, benchmark, fortification structure.

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1. Introduction

In today's conditions, it is difficult to find a branch of economics and research activity in which practical tasks would not arise to study the dynamics of the movement of the upper layers of the earth's surface and the influence of these movements on engineering structures under construction of various profiles, their vital activity during the period of operation, a set of reconstruction measures, if necessary during emergencies and disasters (Zumpano et al., 2018).

This study is devoted to observations of shear processes, the connected movement of earth or rock masses along a sliding surface. Landslides differ from landfalls in that the displaced masses do not lose contact with the bed throughout the process, while during landfalls, these masses pass part of their path in the air.

Landslides are a common geological process that can occur globally. They occur when large masses of soil, stones, or debris move down a slope due to a natural phenomenon or human activity. Landslides can be accompanied by heavy rains, droughts, earthquakes, or volcanic eruptions (Wallemacq & House, 2018). The main elements of a landslide include the sole or a basis of the landslide, landslide tongue, landslide blocks, wall failure, landslide top; failure brow; landslide steps; landslide cracks; zone of sliding (Fell, 1994).

Among the main reasons for the formation of landslides are:
- change of shape and height of the slope;
- change in the structure, condition, and properties of the rocks that make up the slope;
- additional load on the slope (Geology, n.d.; Meddings et al., 2017; Tiranti & Cremonini, 2019).

According to the World Health Organization, landslides have affected approximately 4.8 million people and killed more than 18,000 people since 1998 (World Health Organization, n.d.). Landslides are 5 out of 10 disasters by quantitative indicator after floods, storms, earthquakes, and extreme temperatures (Wallemacq & House, 2018). Climate change and rising temperatures are expected to increase the number of landslides, especially in mountainous areas with snow and ice (Gariano & Guzzetti, 2016). As the permafrost melts, rocky slopes can become more unstable, leading to landslides.

Given the numerous catastrophic situations associated with unstable rock masses and their severe consequences, it is clear that the study of landslide processes is an urgent task.

This study aimed to justify the need and to consider the methodology of stable high-precision observations of the coastal fortification structure, to identify the active landslide zone, and to provide suggestions regarding the features and conditions of further observations. The object of the research is the landslide processes of the coastal zone of the resort city of Ukraine. The subject of the study is the methods and tools for organising observations of dangerous landslide processes in the coastal zone.

From a geostructural perspective, the city of Chornomorsk (Odesa region, Ukraine; 46.288205, 30.655035) is situated on the platform slope of the Black Sea Depression. The coast is of a levelled, complex type, and signs of active abrasion, erosion of accumulative forms, and general retreat of the shore can be seen almost throughout the coast. The area is situated on the north-western wing of the Black Sea depression, which has experienced descending tectonic movements, resulting in the lowering of its surface under sea level and the accumulation of a robust thickness of sedimentary deposits. According to the State Information Geological Fund of Ukraine, the study area has a high complexity of engineering and geological development conditions (State research and production enterprise "Geoinform of Ukraine", n.d.). The territory's geostructural features are reflected in its modern oro-hydrographic features. The crystalline foundation of the platform is composed of various gneisses and granitoids and lies at a depth of approximately 1700 m. Paleozoic, Mesozoic, and Cenozoic sediments of marine origin comprise the sedimentary cover. The surface of the crystalline basement gently dips in the southern direction. The upper, youngest formations that make up the surface of the territory are loess and loess loams, reaching a thickness of 20 m or more in watersheds; below is a layer of red-brown clays, up to 10 m thick, which is covered by a shell limestone layer with a thickness of up to 15 m and more. Frequent landslides on steep seashores are associated with the action of groundwater circulating at the contact of clay and limestone, as well as with the influence of the sea surf.

Different forms of relief can be observed within this territory, with the prevailing natural forms being erosional-accumulative-denudation (watershed plain and its slopes) and erosional-accumulation (river valleys, estuaries, gullies, ravines with slopes, and Black Sea coasts). In addition, there are artificial landforms such as quarries, dams, embankments, pits, and artificial beaches. In general, the territory of Chornomorsk is part of the coastal lowland plain, sloping in the south and southeast and dissected by the valley of the Sukhui Lyman. The plate is crossed by the rivers Dalnyk and Velikodolynske, and several beams were partially smoothed and filled in during the construction process. Closer to the sea, the surface is characterised by a rarer and less deep valley-beam dissection. The sea floods river valleys and creeks in this area.

Plate-like watershed spaces are separated from the sea by steep ledges, and landslides and broken rock blocks often accompany coastal cliffs. The height of the shore ranges from 5–10 m and reaches 25–30 m in some places. Absolute surface marks within the city range from 4 m (sea level cut) to 45–47 m at the watershed. There is a general surface slope towards the sea, with predominant slopes of 2–4% and some areas with more than 20%.

The crystalline foundation of the platform, represented by various gneisses and granitoid, lies at a depth of about 1700 m. Paleozoic, Mesozoic, and Cenozoic sediments of marine origin represent the sedimentary cover. The surface of the crystalline basement gently dips in the southern direction. The upper, youngest formations that make up the surface of the territory are loess and loess loams, reaching a thickness of 20 m or more in watersheds; below is a layer of red-brown clays, up to 10 m thick, which is covered by a shell limestone layer with a thickness up to 15 m and more. Frequent landslides on steep seashores are associated with the action of groundwater circulating at the contact of clay and limestone, as well as with the influence of sea surf.

Visualisation of the territory is shown in Figures 1 and 2, which reflect the image of the current state of the territory and the location on the topographic map.

Physical and geological processes developed in this territory significantly limit urban development possibilities. In the coastal area, in addition to urban planning, recreational functions are also essential to ensure the social function of the population and the economic and environmental effects. The strategy of greening the development of territories involves identifying negative factors in a specific natural-geographical and socio-economic territory and finding ways to overcome them rationally. A prerequisite for ensuring stable connections between the ecological, social, and economic components of land use development in coastal areas is establishing an ecologically safe space without a threat to life (Bulysheva et al., 2021).

Figure 1. Image of the studied territory of the city of Chornomorsk, Odesa region

Figure 2. Location of the studied territory in the city of Chornomorsk, Odesa region

Landslides are observed in large areas of the Black Sea Basin. Thus, according to research, approximately 33% of the region has a high or very high susceptibility to landslides. Places with the highest or very high vulnerability are located in the western and central regions of the Black Sea (Turan et al., 2020). Consequently, landslides, flooding, abrasion, bank collapse, and erosion are actively developed in the respective territories and adjacent areas. Also, the relevant territories are areas of potential karst development, and there is a possibility of its activation due to the construction of large economic facilities, high seismicity (7–8 points), and sagging soils. Carrying out observations on the slopes ensures the solution of the following two main tasks: studying the mechanism and dynamics of the landslide process and ensuring the safety of the operation of national economic facilities (Mouratidis, 2009). Based on the nature of the tasks, slope observations are classified as geostatic and geodynamic. According to the results of geostatic observations, primary information about the slope is obtained in the form of topographic, geomorphological, and other plans and maps, which are updated and adjusted over time, taking into account the changes that have occurred on the slope.

Geodetic observations allow for obtaining geometrical parameters of landslides. The main requirement for them is the proven accuracy, and this requires an individual approach in each specific case, both to the choice of geodetic observation methods, which are the primary sources of information about the course of the landslide process and to the technology of their implementation (Zeybek et al., 2015). To study the dynamics of landslide slopes, geodetic observations of the movement of a network of landslide points installed on the surface of the landslides are carried out. These observations provide displacement vectors and displacement rates.

Some methods for determining landslide processes have been developed and used in practice, based mainly on applying geodetic methods (Kirschbaum & Stanley, 2018). Geodetic methods offer the advantage of obtaining absolute values of landslides. The main methods include triangulation, trilateration, geodetic marks displacement (direct, reverse, lateral, and distance-angular), polygonometry, satellite determinations, the method of alignments, laser scanning, stereophotogrammetry, geometric and trigonometric levelling. At the same time, the first four methods can be used both independently and in various combinations. Geometric and trigonometric levelling methods always accompany the above methods and complement each other (Mouratidis, 2009).

The main goal of setting up systematic geodetic observations (monitoring) on landslide slopes is to obtain the most complete and reliable information about the kinematic characteristics of landslide development in terms of slope area and time. Achieving this goal is possible only when choosing and implementing (in natural conditions) the optimal design of the geodetic (observation) network and the corresponding method of geodetic observations.

Geodetic monitoring is an essential component of the engineering survey process. The identification and analysis of landslides make it possible to: identify the causes of occurrence and the degree of deformation danger for the normal operation of an object; take timely measures necessary to eliminate the danger; clarify the calculated data on the physical and mechanical properties of soils and limiting deformations. Deformations have a complex mechanism of occurrence and flow. Therefore they are subject to careful study and analysis (Casagli et al., 2016).

Geodetic observations of slope processes during engineering and geodetic surveys are carried out to establish the boundaries of the areas of development of these processes, evaluate and predict quantitative characteristics (values and rates of growth of slope deformations), develop anti-landslide, anti-landslide, and other measures and evaluate their effectiveness in the exploitation of buildings and structures. Observations of slope movements include the determination of vertical and horizontal shifts of points on the surface and in the depth of the slope with a specified frequency, as well as changes in the opening of cracks detected during shear surveying and the slope of individual sections.

Like other types of deformation of slope areas, landslides should be carefully evaluated, and their impact on adjacent areas should be predicted. These observations are made using geodetic methods. Geodetic methods are classified into four groups based on their type, activity, simplicity, and efficiency. These groups include axial, planned, height, and spatial methods.

Axial methods are used when the axes are fixed at three points and are based on relationships with the specified line or axes. These methods are useful for determining the direction and length of a line or for measuring the angle between two lines. An example of an axial method is the triangulation method used to measure the distance between two points.

Planar methods are used to observe the displacement of subsections along two coordinates in the horizontal area. These methods are used to measure the changes in the position of objects on the ground, such as buildings or roads. An example of a planned method is the traverse method used to measure the coordinates of points on the ground.

Height methods are used to indicate only vertical displacements. These methods are useful for measuring the height of an object or the depth of a hole. An example of a height method is the leveling method used to measure the elevation of points on the ground.

Spatial methods are used when more points in space are known due to three coordinates. These methods are used to measure the three-dimensional position of objects, such as buildings or terrain. An example of a spatial method is the Global Navigation Satellite System (GNSS) used to determine the precise location of a point on the ground.

In conclusion, using geodetic methods is essential for various applications such as land surveying, construction, and environmental monitoring. It is important to choose the appropriate method based on the application requirements and the accuracy needed. Phototopographic surveying, laser scanning, and satellite receivers are used to determine the spatial displacement of landslide points. Electronic total stations are used in areas with limited visibility of satellites, where GPS devices and other positioning systems cannot be used. The displacement of observation points is calculated relative to the control marks outside the landslide zone. The number of symbols is determined to accurately measure and define all process characteristics (Zeybek et al., 2015). Observations of landslides are carried out at least once a year. Their periodicity is adjusted depending on the fluctuations in the landslide speed.

2. Materials and methods

In the research process on the territory of the city of Chornomorsk, before the start of topographic and geodetic work, catalogues of coordinates of polygonometry points and steps to the points in the territorial geodetic service were obtained. Four points of polygonometry were determined as the nearest appropriate points to the research object (Table 1). Considering that the method of determining the coordinates of benchmarks at the research object was chosen using GNSS technologies and it is necessary to obtain coordinates in the local coordinate system, a transformation field using the Helmert conformal transformation was created.

Modern geodetic GNSS equipment was used to track dynamic objects during the work. Approximately 200 organizations collect GNSS data from base stations worldwide, united by IGS (International GNSS Service), a part of the International Association of Geodesy. The main existing and promising GNSS systems include GPS (USA), GLONASS (Russia), GALILEO (European Union), BeiDou (China), and QZSS (Japan) (Villiger & Dach, 2021). In many countries, ground-based radio beacon systems are being developed to increase positioning accuracy from several meters to centimetres. Furthermore, radio navigation equipment transmits differential corrections to users, significantly improving the accuracy of determining the coordinates being created. Differential correction is sent from geostationary satellites (WAAS, EGNOS, MSAS, etc.) or ground base stations (Šegina et al., 2020).

The greatest accuracy is achieved when using RTK corrections from ground base stations. Such a network called System.NET has been valid since 2011 in Ukraine. System.NET is a GNSS/RTK network in Ukraine from Leica Geosystems that achieves maximum accuracy of measurements (System.NET, Systems Solutions, & Leica Geosystems, n.d.). To ensure maximum accuracy, a permanent station of the System.NET network was installed directly in the work area, no more than 1 km from the object of study.

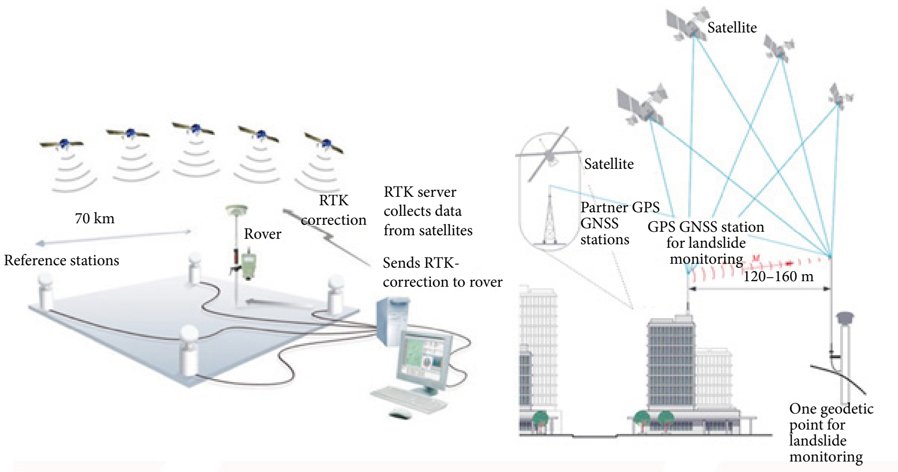
A permanent satellite base station is a hardware and software complex designed to measure and determine the spatial location of objects by providing information for correcting data obtained using satellite navigation, including satellite and communication receivers. It includes computers and other equipment, specialized software installed in the field of measurement and location, and is partially fixed in space permanently and operating continuously. A permanent operating base station includes a GNSS receiver, a satellite antenna, an uninterruptible power supply, communication devices, lightning protection systems,

Table 1. Catalogue of coordinates of initial items of local polygonometry

No	Polygonometry point	Item photo	The coordinates of the localised coordinate system items		
			X (m)	У (m)	H (m)
1	PP Oleksandrivka		–18,575.557	–8,721.544	46.85
2	PP 59		–18,282.124	–8,457.780	38.309
3	PP 46		–17,838.814	–7,286.642	37.666
4	PP 37		–19,860.334	–6,895.754	35.751

and lightning rods installed permanently in a specially prepared place.

The GPS GNSS system of the station operates by continuously observing and determining the station's spatial coordinates using GPS signals (Figure 3) (Haddadi Amlashi et al., 2020). Unlike classical monitoring methods based on optical measurements and one-time binding of tacheometric automated stations to the local coordinate system to determine relative coordinates, the GPS GNSS system has a significant advantage because it determines the absolute coordinates of the measuring station itself with an accuracy of ±1 mm in 24/7 monitoring.



a) b)

Figure 3. The operation principle of the network of permanently operating satellite base stations (a) and the station at the research object (b)

The Bernese GNSS Software, developed by the Astronomical Institute of the University of Bern, Switzerland, was used to process the daily raw observations (Dach et al., 2015). The daily coordinates of the station were obtained as a result of processing GPS observations for September 2018–December 2019.

The study is carried out in two stages. In the first stage, daytime solutions were formed using the Bernese GNSS Software package. The main product of Bernese GNSS Software was a free database solution in the form of a text SINEX format, which contains the parameters for evaluating vector bases and a complete covariance matrix with the coordinates of all points per day. In the second stage, the daily solutions were further sent to the GLOBK software complex for combining data to determine the coordinates of the stations and build graphs of their repeatability (time series), as well as communication with local coordinate systems (Šegina et al., 2020). From the analysis of the obtained results, it became possible to assert that the station has a stable position in time. Inevitable seasonal fluctuations within ±3 mm in the horizontal position and ±5 mm in height due to changes in the temperature regime of the observation point were recorded.

The Baltic height system (BHS77) was used later in the study, with processed and averaged station coordinates in the local coordinate system (X = –21,008.3984; Y = –6,269.0456; H = 78.5670). To conduct direct observations, it was necessary to lay benchmarks on the territory of the research object (see Figure 4 and Figures 5a and 5b).

Figure 4. The scheme of laid ground benchmarks (based on Google Maps, n.d.)

a) b)

Figure 5. Images of benchmarks

3. Results

A coastal fortification was constructed based on a project aimed at protecting the shores of the Black Sea and preventing landslides. The project involved conducting topographical and geodetic surveys of the work area and establishing a permanently operating network station called "System.NET" (System.NET, Systems Solutions, & Leica Geosystems, n.d.).

During the construction of the coastal fortification structure, specially prepared steel rods on the grid were installed to set construction milestones for monitoring with a total electronic station, which was mounted in places at the height of 10 mm above the grid screed.

During the shooting, the receiver antenna on specially prepared screws was mounted. Thus, with the help of "forced" centring, it was possible to get high-precision data and practically avoid centring errors (up to 1 mm). Ground geodetic benchmarks were observed with a Leica GS08 GNSS receiver in static mode for 60 minutes, which ensured high accuracy of the measurement results. The stages and content of the work for laying and investigating the ground benchmarks are presented in Table 2.

After analyzing the results of the entire cycle of observations, it was determined that nine benchmarks (B5, B6, B9, B11/1, B12, B13, B17, B18, and B33) had been displaced in the southeast vector as a result of the landslide. The minimum deviation during the observation period was 0.04 m (B11/1), and the maximum was 6.43 m (B5), with B5 having the largest deviation of 16.52 m.

To protect the coastal strip and prevent landslides, the city administration decided to construct a coastal fortification structure in the coastal zone. A total of 53 geodetic benchmarks were laid on it, and monitoring of these benchmarks was carried out simultaneously with the observation of ground benchmarks.

Figures 6 and 7 show a scheme of the embedded geodetic benchmarks on the grid of the pile row of the coastal fortification structure and the displacement and velocity vectors displayed on a map for the final period of observations. It should be noted that there was a need to destroy and add new benchmarks in previous periods, as described above in the research.

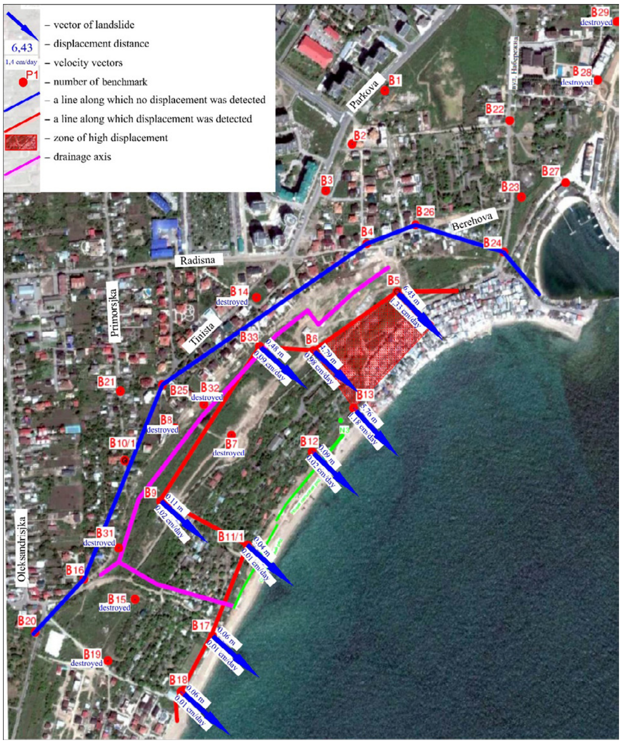


Figure 6. Displacement and velocity vectors of benchmarks with their display on the map from September 2017 to April 2020

Monitoring of the installed geodetic benchmarks on the coastal fortification structure was started from the moment the construction of this structure began and was carried out once a month. The geodetic benchmarks on the coastal fortification structure were observed by a Trimble M3 electronic total station from a pair of benchmarks, the coordinates of which were determined by the Leica GS08 GNSS receiver, in static mode, for 60 minutes, monthly, before each total station observation. Figure 8 illustrated the initial scheme of geodetic benchmarks laid on the coastal fortification structure.

Table 2. Stages and content of works for laying and investigation of ground benchmarks

Period	Work content	Benchmarks	Displacement direction	Displacement degree
September 2017–November 2017	Installation of 14 benchmarks, monthly observations of all installed benchmarks	B1-B14	Southeast, except for B1, B2, B3, B4, B14 (were not displaced)	The minimum deviation is 0.05 m (B10), and the maximum is 0.62 m (B13)
December 2017–January 2018	Installation of 11 benchmarks, observations of all installed benchmarks	B15-B25	Southeast in B5, B6, B7, B8, B9, B10, B11, B12, B13, B15, B17, others were not displaced	The minimum monthly deviation was 0.023 m (B15), maximum deviation – was 0.120 m (B5)
February 2018–November 2019	Installation of 5 benchmarks, observations of all installed benchmarks	B26-B30	Southeast in 10 benchmarks (B5, B6, B7, B8, B9, B12, B13, B18, B19, B11/1), others were not displaced	The minimum deviation is 0.01 m (B19), and the maximum deviation was 0.32
November 2019–July 2020	Installation of 3 benchmarks, monthly observations of all installed benchmarks	B31-B34	Southeast in 8 benchmarks (B5, B6, B9, B12, B13, B24, B32, B33)	The minimum deviation is 0.02 m (B9, B12, B24, B32), and the maximum is 0.68 m (B5)

The installation of geodetic benchmarks on the grid of the coastal fortification structure and their monitoring was carried out gradually, simultaneously with the construction of this structure (Table 3).

The absolute displacement values for the main benchmarks on the coastal fortification structure during the entire observation period are presented in Table 3, considering the destruction of some benchmarks due to weather conditions, technical issues, or other reasons (in order to decrease the displacement index and highlighting objects with final displacements greater than 0.1 m). Additionally, Figure 9 illustrates displacement vectors and a quantitative indicator of displacement for the last observation period, accounting for changes in the number and location of benchmarks during the study. The dynamic of the displacement absolute value for the main benchmarks on the grillage of the coastal fortification structure is shown in Table 4.

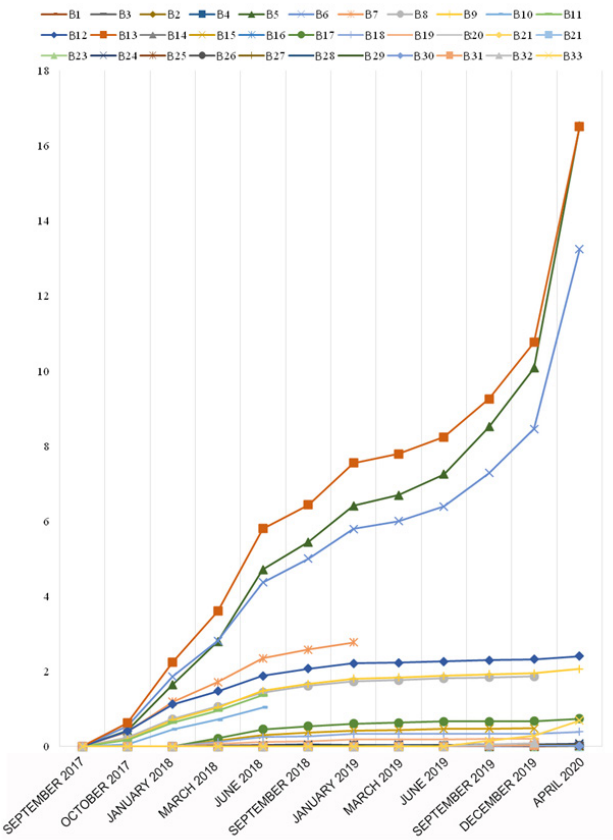


Figure 7. Graphic display of quarterly absolute deviation of ground benchmarks (formed based on the results of own research)

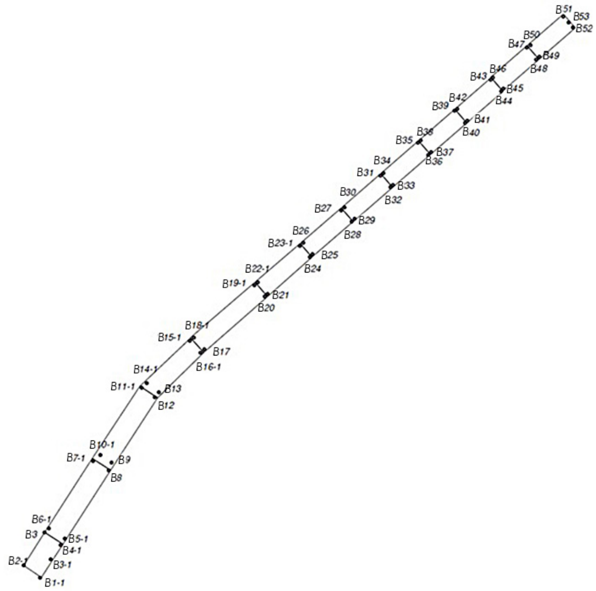


Figure 8. Scheme of geodetic benchmarks laid on the coastal fortification structure

Table 3. Stages and content of works for laying and studying benchmarks on the coastal fortification structure

Period	Work content	Benchmarks	Displacement direction	Displacement degree
January 2017–April 2018	Installation of 16 benchmarks, monthly observations of all installed benchmarks	B1-B16	Southeast	B2 – 3 cm, B16 – 2 cm, other benchmarks – 1 cm
May 2018–August 2018	Installation of 16 benchmarks, monthly observations of all installed benchmarks	B16-B32	Southeast	B10 – 3 cm, other benchmarks – 1 and 2 cm
September 2018–October 2018	Installation of 8 benchmarks, monthly observations of all installed benchmarks	B33-B40	Southeast	The minimum deviation was 0.09 m (B12, B13, B16-1), and the maximum was 0.16 m (B6-1, B31, B32)
November 2018–April 2019	Installation of 13 benchmarks, monthly observations of all installed benchmarks	B41-B53	Southeast	The maximum deviation was 0.01 m (B8, B9, B12, B16-1, B20, B21, B24, B28, B29, B36, B37, B40, B41, B45), other benchmarks were not displaced
May 2019–February 2020	Monthly observations of all installed benchmarks	B1-B53	Southeast	All benchmarks had a displacement within 1 cm
March 2020–April 2021	Suspension of observations	B1-B53	–	–

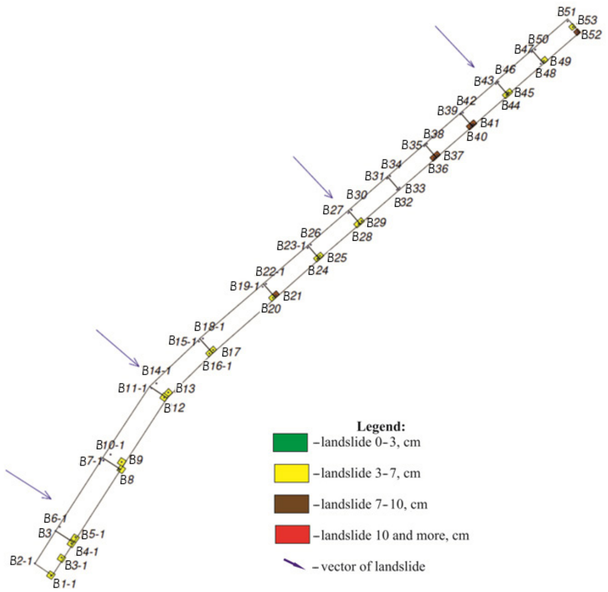


Figure 9. Displacement vectors and a quantitative indicator of the displacement of benchmarks on the coastal fortification structure for the last observation period

Regarding the accuracy assessment, the measured quantity's actual value was known, and the mean squared error (m) of a separate result of equal-precision measurements was determined by the Gauss formula. Before each monthly observation of embedded benchmarks began, four points of the State Geodetic Network (SGN) were removed, along which a transformation field was created. During the entire period of observation, 52 measurements of each point of the SGN were performed. To calculate the RMS error, quarterly measurements were chosen. The determination of the RMS error of the Oleksandrivka polygonometry point, points of polygonometry PP46, PP37 and PP59, is given in Table 5.

Analysing the obtained research results, we can conclude that the maximum RMS for determining the horizontal position of polygonometry points was 12 mm at point PP37. The average arithmetic RMS of determining the horizontal position of the points of polygonometry in all dimensions is 9 mm. The maximum RMS determining the height position of polygonometry points was 14 mm at point PP46. The average arithmetic RMS of determining the height position of the points of polygonometry in all dimensions is 13 mm.

Table 4. Dynamics of the displacement absolute value for the main benchmarks on the grillage of the coastal fortification structure in the order of decreasing the displacement index and with a final displacement greater than 0.1 m

Number of benchmark	February 2017	April 2017	June 2017	September 2017	January 2018	March 2018	June 2018	September 2018	January 2019	March 2019	June 2019	September 2019	December 2019	January 2021
B37					0.25	0.38	0.57	0.68	0.84	0.87	0.90	0.91	0.94	1.02
B36					0.25	0.37	0.57	0.68	0.83	0.85	0.89	0.91	0.93	1.01
B40					0.30	0.41	0.55	0.64	0.80	0.82	0.86	0.87	0.90	0.98
B8	0.00	0.02	0.04	0.06	0.37	0.52	0.64	0.70	0.80	0.83	0.85	0.88	0.89	0.94
B9	0.00	0.02	0.03	0.05	0.36	0.51	0.63	0.69	0.79	0.82	0.84	0.87	0.88	0.93
B29				0.06	0.31	0.37	0.56	0.65	0.77	0.80	0.82	0.84	0.86	0.92
B24				0.04	0.30	0.41	0.58	0.66	0.76	0.80	0.81	0.84	0.85	0.91
B28				0.04	0.29	0.36	0.55	0.64	0.76	0.79	0.80	0.82	0.84	0.91
B25				0.04	0.29	0.39	0.56	0.64	0.75	0.78	0.79	0.81	0.83	0.90
B20				0.03	0.29	0.39	0.56	0.63	0.74	0.76	0.79	0.80	0.82	0.89
B21				0.02	0.28	0.39	0.54	0.62	0.73	0.75	0.77	0.79	0.81	0.88
B12	0.00	0.03	0.06	0.07	0.31	0.43	0.57	0.63	0.73	0.75	0.77	0.80	0.81	0.87
B13			0.02	0.05	0.28	0.40	0.54	0.60	0.69	0.72	0.74	0.76	0.78	0.83
B16				0.03	0.26	0.38	0.51	0.58	0.68	0.71	0.72	0.75	0.77	0.83
B17				0.02	0.25	0.36	0.50	0.52	0.57	0.62	0.69	0.76	0.76	0.82
B41					0.03	0.10	0.22	0.31	0.44	0.46	0.49	0.50	0.53	0.60
B44					0.02	0.04	0.09	0.12	0.22	0.24	0.27	0.27	0.29	0.35
B45							0.04	0.08	0.17	0.18	0.21	0.21	0.23	0.29
B5	0.00	0.02	0.04	0.08	0.46	0.61	0.71	0.47	0.07	0.09	0.11	0.14	0.14	0.20
B4	0.00	0.02	0.04	0.08	0.45	0.60	0.73	0.52	0.06	0.09	0.10	0.12	0.14	0.18
B52							0.02	0.04	0.05	0.06	0.09	0.09	0.09	0.16
B53							0.01	0.03	0.05	0.06	0.09	0.09	0.10	0.16
B3	0.00	0.02	0.04	0.08	0.07	0.07	0.07	0.06	0.05	0.07	0.08	0.10	0.12	0.15
B49							0.01	0.03	0.05	0.06	0.07	0.08	0.09	0.14
B1	0.02	0.04	0.04	0.11	0.48	0.61	0.60	0.30	0.04	0.06	0.07	0.08	0.09	0.11

Table 5. Determination of the RMS

Observation date	Oleksandrivka polygonometry point			Point of polygonometry PP59			Point of polygonometry PP46			Point of polygonometry PP37		
	Δ = X′ – X	Δ = Y′ – Y	Δ = H′ – H	Δ = X′ – X	Δ = Y′ – Y	Δ = H′ – H	Δ = X′ – X	Δ = Y′ – Y	Δ = H′ – H	Δ = X′ – X	Δ = Y′ – Y	Δ = H′ – H
15.02.2017	–0.006	–0.010	0.008	0.011	–0.005	0.008	0.013	–0.014	–0.012	0.013	0.013	–0.018
01.06.2017	0.005	–0.012	0.012	–0.009	–0.013	–0.013	0.010	–0.007	–0.019	0.004	–0.015	–0.012
18.09.2017	0.009	0.002	0.003	0.002	–0.016	0.009	–0.013	–0.007	0.010	0.008	–0.012	0.007
23.01.2018	–0.008	–0.007	–0.016	–0.005	0.009	0.014	–0.005	0.011	–0.015	–0.011	0.011	0.012
21.04.2018	0.011	0.010	0.003	0.007	0.010	0.010	0.005	0.001	0.011	0.003	–0.005	0.006
01.10.2018	0.003	0.001	–0.013	0.006	–0.004	0.009	0.016	0.009	–0.008	–0.012	0.017	–0.006
30.01.2019	–0.010	–0.015	0.014	–0.015	–0.009	0.013	0.011	–0.013	0.011	–0.006	–0.007	–0.008
12.06.2019	–0.008	0.012	–0.007	0.003	0.003	0.010	–0.013	–0.004	0.018	0.007	–0.006	0.016
10.12.2019	0.008	–0.004	–0.012	–0.002	0.012	0.017	–0.006	0.007	–0.011	0.012	0.010	0.015
10.04.2021	0.007	–0.007	0.018	0.000	–0.011	–0.011	0.006	0.002	–0.018	–0.005	–0.013	–0.017
RMS (m)	0.008	0.009	0.012	0.007	0.010	0.012	0.011	0.009	0.014	0.009	0.012	0.013
Measurement error of RMS (M)	0.002	0.002	0.003	0.002	0.002	0.003	0.002	0.002	0.003	0.002	0.003	0.003

4. Discussion

The ratio of ground benchmarks to coastal fortification benchmarks is debatable and depends on the area's conditions and relevance. Additional studies should be accompanied by analysing a specific territory, considering a particular area's geological, geomorphological, and ecological characteristics.

Research frequency and the need for continuous measurements considering displacement parameters, the decommissioning of some benchmarks, and the effectiveness of their installation scheme are debatable. A set of equipment components for monitoring landslide processes will be compared. Dabove et al. (2020) explore the possibility of using mass-market GNSS receivers and antennas for networked real-time kinematic positioning for displacement detection. The dependence of the duration of monitoring on the climate and geomorphology of the territories is also debatable and requires further research. Thus, Saleh and Al-Bayari (2007), conducted measurements annually only at two different times – before and after the rainy season.

5. Conclusions

The proposed methodology and volume of the landslide monitoring system provided reliable and sufficiently complete information for the preparation of a conclusion about the current state of the landslide, the nature, and the direction of its movement, as well as a forecast of its condition for the near future. The geodetic monitoring of anti-landslide measures to protect the slope and its stability was analysed during the research. Based on the monitoring results, the spatial and temporal parameters of the displacements of ground benchmarks and geodetic benchmarks on the grillage of the coastal fortification structure of the slope were determined. Relevant data are necessary to ensure the direction of further work on preventing landslide processes, protecting territories from danger, and the harmonious process of using land resources in recreational or urban planning directions, depending on the general and detailed plans of territories and legislative regulations.

The advantages of using GNSS equipment for monitoring slope deformations compared to traditional geodetic methods have been identified:

- no need for direct visibility between points;
- achievement of high accuracy in determining the coordinates of points;
- the unified coordinate system of observation results without the need for recalculations;
- providing complex acquisition of coordinates (horizontal and high-altitude);
- increasing the degree of automation of field and office work in comparison with visual methods and also non-geodetic techniques (Liu & Wang, 2008);
- increase in safety of personnel performing observations.

As a result of the analysis of the phasing and conditions of the study to ensure the sustainable development of the coastal areas, it is recommended to continue the observations monthly (maximum quarterly – considering previous data and seasonality) to control landslide processes and deformation of the shore fortification structure; update of coastal engineering protection schemes; recovery (based on the analysis of geodetic monitoring data) and maintenance of coastal fortification structures in working condition, restoration of regular large-scale monitoring of exogenous processes in the coastal strip to ensure sustainable development of coastal areas, taking into account the social, economic and ecological needs of residents.

Author contributions

DB and IL conceived the study and were responsible for the design and development of the data analysis. OM and TM were responsible for data collection and analysis. OV was responsible for data interpretation. OP wrote the first draft of the article.

Disclosure statement

Authors state that they have any competing financial, professional, or personal interests from other parties.

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