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JUSTIFICATION OF GEODETIC MONITORING METHODOLOGY OF THE RETAINING WALLS ON THE EXAMPLE OF THE EMBANKMENT IN KREMENCHUK

Purpose. Development of a methodology for analyzing the results of geodetic measurements according to which it is possible to use the materials of past years for the needs of geodetic monitoring on the example of a retaining wall in the conditions of the city's recreational area.

Methodology. A technological scheme of geodetic monitoring of retaining walls has been developed with four main stages: analysis of initial data, design of geodetic monitoring, periodic observations, processing and analysis of geodetic monitoring results. The conditions of the recreational areas of the city determine the specifics of geodetic monitoring, limit the possibilities of choosing a scheme of the geodetic network and methods of measurements. In this regard, it is proposed to develop models of the development of deformation processes already at the first stage of geodetic monitoring, which will allow geodetic monitoring to be carried out with greater reliability in the future and avoid possible forecasting errors.

Findings. The results of the analysis of geodetic measurements in the geodetic networks of Kremenchuk (coordinates and heights of wall signs) show the presence of horizontal and vertical displacements of the retaining wall. In the horizontal plane the retaining wall has shifted in the south-western direction, towards the Dnipro River. In the vertical plane, the retaining wall has subsided. The displacements of different parts of the retaining wall are uneven. The average annual rate of both horizontal and vertical displacements is equivalent and is approximately 1 mm/year. The values of absolute displacement vectors of wall signs in the horizontal plane exceed the accuracy of geodetic measurements and normative tolerances.

Originality. Modeling of displacements of retaining walls in the conditions of recreational areas of the city is already underway, taking into account the analysis of the results of geodetic measurements of past years.

Practical value. The data of the analysis of the results of geodetic measurements carried out in the geodetic densification networks of Kremenchuk indicate the presence of deformation processes and justify the need for their control through geodetic monitoring. The suggested models can be used as the comparative and combined analysis of future forecast changes based on previous and current results of measurements, which is a topic for another research.

Keywords: *geodetic monitoring, retaining wall, wall sign*

Introduction. At the stage of operation of buildings and structures, their technical condition can be affected by negative atmospheric and geological processes and phenomena. In particular, geodynamic processes of a local, regional or global nature can lead to their deformations.

The modern level of development of classical and satellite geodetic technologies and devices, as well as the accuracy and quality of geodetic observations, provides an opportunity to determine and monitor even very minor local changes in the spatial position and orientation of the objects being studied. Geodetic monitoring is the main source of information about the quantitative characteristics of deformations of buildings due to various factors.

Geodetic monitoring is a complex of periodic geodetic observations of the geometric parameters of bases, foundations and above-ground building structures, spatial displacements of buildings and structures, the dynamics of the development of deformations at the stages of construction and operation, the development of destructive geological processes (erosion, landslides, karst, suffusion phenomena, subsidence of the earth surface).

Spatial-temporal analysis of monitoring results allows one to assess the inconsistency of the actual and design parameters of buildings and structures, to identify regularities and predict the movement of the earth's surface, buildings and structures in a timely manner, to make timely management decisions to prevent the manifestation of dangerous processes, to model measures of engineering protection of buildings and structures. The correct interpretation and use of information about deformations of technological equipment, buildings and structures, obtained as a result of geodetic monitoring, contributes to the improvement of conditions and increases the safety and term of their operation. Therefore, the development and improvement of geodetic monitoring technologies, in particular of various types of buildings and structures, is an up-to-date direction of scientific research.

The method for performing geodetic monitoring should ensure the necessary accuracy. The accuracy of determining the position of the reference points of the monitoring network should usually be 1.5 times higher than the accuracy of determining the points on the investigated building or structure.

Special attention during the implementation of measures to counter landslide processes is paid to the construction and subsequent monitoring of retaining walls, which are engineering structures that differ in their functional purpose, class of consequences, material, manufacturing method, and shape of the transverse profile. Retaining walls of general purpose, hydrotechnical, industrial, as well as special retaining anti-slide and anti-landslide retaining walls are distinguished by purpose.

Detection and assessment of deformations of retaining walls in time and space is of engineering and technical importance to prevent a gradual decrease in their reliability. Today, the unsolved parts of the general problem are the modeling of horizontal and vertical displacements of retaining walls, which are in imperceptible dynamics in the conditions of recreational areas, based on the analysis of a small number of initial measurements. The purpose of this study is to develop a methodology for analyzing the results of geodetic measurements for the needs of geodetic monitoring of retaining walls in the conditions of recreational areas of the city. The study involves the development of a technological scheme for monitoring retaining walls located in the conditions of recreational areas of the city and the analysis of the results of geodetic measurements of past years on the specific example of the city of Kremenchuk.

Methods. The following scientists are engaged in the search for ways to solve the current problems of engineering geodesy related to earth movements and deformations of buildings and structures: Hladilin V., Hryhorovskyi P., Isaev O., Tretiak K., Hailak A., Shulz R., Bauer P., Zygmunt M., Lepădatu D., Liu B., Sztubecki J., Yuwono B. D., etc.

Modern measuring technologies make it possible to perform tasks that were previously impossible to solve with the help of conventional traditional methods. At the same time, they reduce time spent and provide higher measurement accuracy [1].

Important parameters of geodetic monitoring are the speed and direction of deformations, therefore, in each specific case, it is necessary to select the optimal monitoring method to obtain reliable information about the behavior of the structure. The modern practice of geodetic monitoring has singled out its methods, which are used depending on specific tasks:

- high-precision leveling, trigonometric leveling, hydrostatic leveling [2, 3], microleveling (investigation of subsidence of buildings and structures);
- application of sensors to control the opening of cracks in real time [4, 5];
- linear and angular measurements (research on horizontal displacements, subsidence, roll, deflection and torsion of buildings, structures and technological equipment; monitoring of geodetic network points) [5, 6];
- terrestrial laser scanning (study of subsidence, tilting and deflection of buildings and structures) [1, 7];
- inclinometry (control of horizontal displacement of structures) [5];
- photogrammetric (study of subsidence and tilting of buildings and structures) [2, 7];
- construction of the vertical by means of vertical projection devices, the method of reverse slopes, video measuring and video hydrostatic methods (research of roll and torsion of buildings and structures) [7];
- the use of automated geodetic monitoring systems, in particular, for the control of structures of engineering structures of hydropower plants in order to detect and prevent potentially dangerous processes [8];
- global navigation satellite observations (GNSS) for the study of geodynamic processes, subsidence, roll and torsion of high-rise buildings, search for points of geodetic networks on the terrain [4, 9].

Scientific research gradually expands the scope of application of well-known methods and offers innovative methods for processing their results and forecasting to solve certain scientific tasks.

The choice of a specific observation method or a set of methods depends on the available observation conditions, the required accuracy of displacement determination and the speed of spatial movements of structures.

Static GNSS is used [10] to study the vertical movements of land corresponding to the geological structure of coastal and river areas in northwestern Poland, using the example of engineering structures.

Non-stationary non-automated geodetic monitoring systems are used for periodic control of slowly developing processes, but do not provide information about the state of the research object between observation cycles [2].

The concept of permanent geodetic monitoring on a construction site in a 3D environment using virtual reality, built-in sensors, electronic total stations and BIM technology is considered in [11] on the example of a railway tunnel. It represents an improvement of the traditional practice of using only two-dimensional CAD plans for the design of geodetic monitoring.

A combination of methods is often used to monitor the intensity of uneven landslides. GNSS surveying and terrestrial laser scanning are used [12] to monitor the deformations of hydrotechnical structures. The technology of geodetic monitoring with the complex application of ground laser scanning, shooting from a UAV and robotic total stations is used [13] for a multi-criteria analysis of a linear engineering structure at the stage of operation.

One of the defining parameters of geodetic monitoring is the periodicity of observations, which does not depend on the total duration of observations but may differ for different stages of the life cycle of a building or structure. Studies on deformations of buildings and structures for scientific purposes are carried out monthly [14], weekly [15], once or twice a quarter (during construction), once or twice a year (during operation) [2], every three months during the change of seasons [16] or with other periodicity depending on the existing conditions and monitoring tasks.

Usually, observations are completed when the values of displacements in the last three cycles do not exceed the accuracy of measurements [16]. The obtained data are compared with the maximum permissible values, taking into account the provisions of regulatory documents (for hydraulic structures [17, 18]).

Requirements for the accuracy of geodetic monitoring of buildings and structures are characterized by root mean square errors (RMS) depending on the geological structure [2]: on rocky soils – 1 mm; on sandy, clay and other soils – 3 mm; on bulk and other highly compressible soils – 10 mm; for earthen structures – 15 mm; on sliding areas – 10 mm (horizontal displacements) and 30 mm (settlement).

The work [19] describes the technology for assessing the degree of reliability of geodetic points and the possibility of using them as reference points for increasing the accuracy of geodetic monitoring of processes, phenomena, buildings and structures. The selection of stable geodetic points of the local monitoring network is proposed to be carried out by interval estimation of the errors of determining their coordinates in accordance with the required level of reliability, which depends on the class of consequences of the monitoring object.

In the article [20], in order to improve the design of geodetic monitoring, it is proposed to determine the accuracy and reliability criteria of geodetic deformation monitoring networks based on the accuracy of deformation parameters.

To optimize the systematic error of measuring deformations of industrial structures by linear-angular methods with robotic electronic total stations, the simplex method is used [21].

Modern geodetic technologies, in particular, mobile applications of well-known geodetic programs, simplify mathematical processing of the results of monitoring of buildings and structures [22].

To evaluate the results of geodetic monitoring, a number of methods of mathematical modeling and forecasting of displacements of buildings and structures are used. Polynomial, exponential, and trigonometric models based on the method of least squares are the most common in displacement monitoring practice. At the same time, the nonlinear method of neural networks is considered one of the promising methods of processing the results of the monitoring of buildings [14].

Structural mechanics methods are used to assess deformation processes, in particular, the finite element method [4, 20].

Another approach considers static, kinematic and dynamic deformation models as physical processes [23, 24]. The problem of modeling deformation processes can be solved using deductive logical-mathematical or inductive methods. Deductive and simulation methods are convenient for simple modeling tasks, if the physical theory of the object under study is well defined, for which a physical model can be developed. For the study of complex processes and objects, which are characterized by insufficient, unclear or short initial information, with a significant number of monitoring parameters, a suitable option is the construction of a kinematic model, which presents the displacement as a function of time, and not of loads. The inductive method of group consideration of arguments provides an opportunity to obtain information about the monitoring object directly from the data sample. This approach is based on the evaluation of models according to a number of criteria that gradually become more complicated [23].

The disadvantage of kinematic models of deformations is the unequivocal mathematical relationship between the physical cause of the deformation and the geometric effect on the object. The most complete deformation of industrial equipment is described by the dynamic model [24].

A single displacement model can be used only in case of uniform displacement of the entire monitoring object (buildings and structures) [15]. At the same time, the most dangerous are uneven and partial displacements [25].

Results. The main goal of geodetic monitoring of retaining walls is to determine changes in geometric characteristics (vertical and horizontal displacements, speed and direction of displacements), and forecast the development of deformation processes.

Taking into account the monitoring schemes proposed in scientific studies [3, 7], a scheme of the technological process of geodetic monitoring of retaining walls in the conditions of recreational areas was developed, which depicts the main stages and tasks of geodetic monitoring (Fig. 1).

The conditions of recreational areas determine the specifics of conducting geodetic monitoring, including complicating the conditions of visibility and performing geodetic measurements on the terrain. In particular, the park zone regime will make it difficult to use stationary automated monitoring systems, if they become necessary. Accordingly, non-stationary non-automated monitoring methods are preferred. From the point of view of convenience, the best method in such conditions appears to be the use of periodic GNSS.

To investigate deformations, wall signs or film reflectors are installed on buildings and structures. Wall signs (marks, benchmarks) for fixing the working points of the monitoring network must be universal, able to provide the possibility of installing a GNSS receiver, a reflector, a sighting mark, a leveling rail, a hanging rail and determining both the planned and the height displacement of the structure over time during the entire period observations.

Reference points of geodetic networks require an assessment of the reliability of their static state, ability to respond to various factors to determine the possibility and expediency of use for the needs of geodetic monitoring.

The analysis of the measurement results of previous years is performed in order to assess the nature of the development of deformation processes [10]. For its implementation, technical reports, catalogs, plans, profiles, projects and other documentation are collected. Such an analysis of source materials is performed once during the entire observation period. According to its results, the parameters (accuracy and periodicity of observations) and technologies of geodetic monitoring

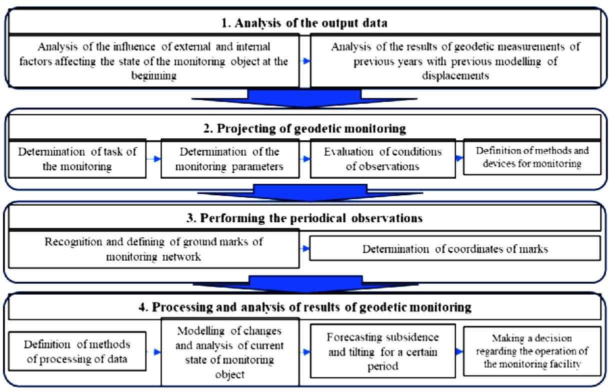

Fig. 1. Scheme of the technological process of geodetic monitoring of retaining walls in the conditions of recreational areas

should be determined. As is known, the model of deformation processes of a building, structure, equipment, or the earth's surface is determined by the displacement vectors of their fixed points determined by control points [25, 26].

The horizontal displacements of the point display the vectors ΔX and ΔY along the X and Y coordinate axes, respectively, and the absolute horizontal displacement vector S. The displacement in the vertical plane shows the vector ΔH. The displacement in all directions (in space) reflects the vector f [26].

Horizontal displacements of a separate point of a building or structure are determined by formulas

$$\Delta X = X_{cur} - X_{in}; \quad (1)$$

$$\Delta Y = Y_{cur} - Y_{in}, \quad (2)$$

where X_{cur}, X_{in}, Y_{cur}, Y_{in} are coordinates of the point in the current and initial cycles of observation along the axes X and Y respectively.

The absolute horizontal displacement vector is calculated using the formula

$$S = \sqrt{\Delta X^2 + \Delta Y^2}. \quad (3)$$

The vertical displacement of a point is defined as the difference between its marks in the current and initial observation cycles [25]

$$\Delta H = H_{cur} - H_{in}, \quad (4)$$

where H_{cur} and H_{in} are point marks in the current and initial observation cycles, respectively.

Average vertical displacement of a building or structure ΔH_{av} is determined by the formula

$$\Delta H_{av} = \frac{\sum H_i}{n}, \quad (5)$$

where $\sum H_i$ is the sum of vertical displacements; n – the number of points.

The displacement vector of a point in space is calculated according to the formula

$$f = \sqrt{\Delta S^2 + \Delta H^2}. \quad (6)$$

Average speed of vertical displacement V_{av} is calculated according to the formula [2]

$$V_{av} = \frac{\Delta H_{avj} - \Delta H_{avi}}{t}, \quad (7)$$

where ΔH_{avj} is the average vertical displacement of the building or structure in the j-cycle of observations; ΔH_{avi} is average vertical displacement in the previous i-cycle; t is the observation period between the i- and j-cycles.

Relative displacement of points η, which can cause a change in the size and shape of the object, is calculated according to the formula

$$\eta = \frac{\Delta H_a - \Delta H_b}{L}, \quad (8)$$

where L is the distance between points with displacements ΔH_a and ΔH_b.

The object of the study is the retaining wall of the embankment between the Rock – granite register and the street. Troitska on the territory of "Prydniprovskyi" park on the left bank of the city of Kremenchuk (Figs. 2, 3). According to the zoning scheme of the city of Kremenchuk, the park is located in the landscape-recreational zone of greening for public use (city parks, squares, boulevards, embankments).

The retaining wall under study is a permanent enclosing hydrotechnical structure, built on a natural foundation, on rocky and sandy soils and designed to absorb pressure from the lateral pressure of water.

The height of this massive monolithic engineering structure is 4.5 m, the width is 0.6 m, and the length is 770 m. The

Fig. 2. The exterior of the research object (*during the spring flood, April 2023*)

Fig. 3. The territory of the location of the research object

retaining wall was built from local building materials of granite (rubble) in the late 1920s and early 1930s to protect low-lying areas of the city from floods. A visual inspection (Fig. 2) revealed that the retaining wall has cracks in some places caused by the adverse effects of the external environment during its more than ninety-year period of operation. Taking into account the technical parameters (height and type of soil of the base) by the class of consequences (responsibility), the investigated retaining wall belongs to objects of the *1st* class [18] with insignificant consequences of failure (object level).

The characteristics of the points of the urban geodetic network of condensation and SGN, located along the embankment of Kremenchuk (Figs. 3, 4), are given in Table 1.

The points of the urban geodetic network of densification (Table 1) belong to one line, fixed by ground and wall geodetic marks and centers.

Most of the items belong to one accuracy class (1 digit). Two points of higher classes (VIgr and VIIIgr) were used as exit points. Wall signs are fixed in the upper part of the retaining wall. The coordinates of the wall signs were determined by the polar method from temporary centers, which are now lost. Markings of wall signs were also determined from temporary centers.

Errors in determining the plan and height position of geodetic points by different methods in different years did not exceed the normatively established maximum permissible values of accuracy parameters for geodetic networks of *4th* class, *1st* grade and leveling networks of the IV class.

Indicators of the accuracy of geodetic measurements in 2018 (mean square errors (MSE) of determining the planned position of points) are summarized in Table 2.

Measurements of excesses were generally characterized by the largest SCP determination of the height position of the point at the weakest point of the stroke at the level of 0.014 m per 1 km of the double leveling stroke. The results of observations and their analysis are often presented in tabular and

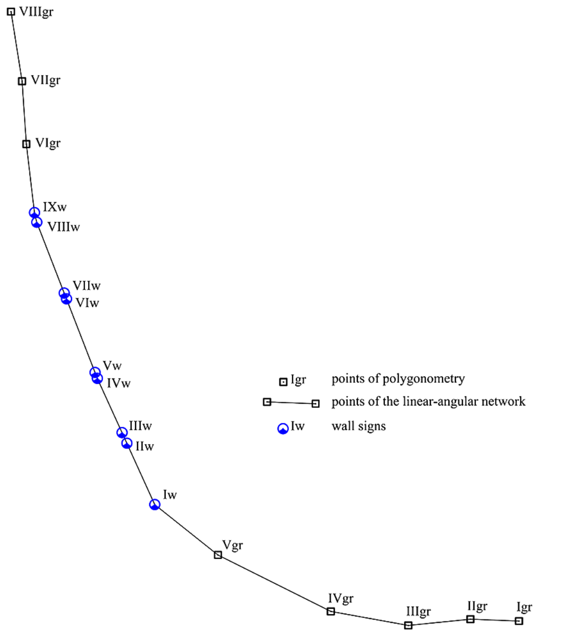

Fig. 4. Scheme of the existing geodetic base along the embankment of Kremenchuk

Table 1

Characteristics of the points of the geodetic network in the area where the research object is located

Name	Network class/category	Type of center/mark
Igr	1 category	6 gr
IIgr	1 category	6 gr
IIIgr	1 category	6 gr
IVgr	1 category	mark in the concrete
Vgr	1 category	mark in the concrete
Iw	1 category	8 gr
IIw	1 category	III
IIIw	1 category	III
IVw	1 category	III
Vw	1 category	III
VIw	1 category	III
VIIw	1 category	III
VIIIw	1 category	III
IXw	1 category	III
VIgr	3 class	1 gr
VIIgr	1 category	mark in the concrete
VIIIgr	4 class	6 gr

graphic forms [27]. Markings of wall signs and their subsidence, determined in the conventional coordinate system based on the results of measurements of excesses by the method of geometric leveling of the IV class, carried out in the geodetic networks of Kremenchuk, summarized in Table 3.

The average vertical displacement for the period 1982–2000, determined according to the data in Table 3 according to formula (5), is 21 mm.

The average rate of vertical displacement of the retaining wall, calculated by formula (7), is 1.2 mm/year. Accordingly, the intensity of subsidence can be characterized as low. Relative settlement of the retaining wall between wall marks Iw and IXw during 1982–2000, calculated according to the formula (8), equals 1/33110 (0.00003).

The analysis of the rectangular coordinates of the points of the urban geodetic network of the city of Kremenchuk in the area of the embankment in "Prydniprovskyi"park, obtained by the results of geodetic measurements during its creation, reconstruction, inventory and survey for the period 1982–2018, is given in Tables 4, 5.

The coordinates of the points (Tables 4, 5) are brought to a unified conventional coordinate system based on the coordinates defined in LSC53 (2018) and transformed to LSC53 (1982 and 2000) in the Digitals program. The differences between the initial and last cycles of observations are shown in Table 6. The model of the subsidence of the retaining wall for 1982–2000 is shown in Fig. 5.

In Figs. 6, 7, there are graphically displayed schemes of planned displacements of wall signs of the retaining wall for the period 1982–2018 along the X and Y axes, respectively.

The displacements of wall signs (Figs. 5–7) are uneven and differ in absolute values.

The nature of the subsidence of wall signs (Fig. 5) is approximated by a polynomial function of the fourth degree with a sufficient degree of approximation reliability.

According to European practice [28], the settlement of the base up to 25 mm guarantees absolute reliability for the entire period of operation of the building or structure.

The model of the displacement of the retaining wall in the horizontal plane for the period 1982–2018 is shown in Fig. 8 (the transverse scale of which is 1,000 times greater than the longitudinal).

As can be seen from Fig. 8, between the first (initial) and second, and second and third cycles of observations, the retaining wall moved almost equally in area, which indicates almost the same intensity and certain uniform patterns of displacement of the retaining wall for the same time intervals from 1982 to 2018. During this period, half of the retaining wall between the Vw and Iw wall marks moved by 40–61 mm, and the other half (between the IXw and Vw wall marks) – by 15–40 mm, that is, 1.5–4 times less. This can be explained by the presence of shore-reinforcing concrete blocks in front of that half of the retaining wall, placed to reduce the harmful effects of the kinetic energy of the water. The other half of the retaining wall (between the Vw and Iw wall marks) is separated from the Dnipro River by a washed-up beach.

Compared to other sections of the retaining wall, the section between the wall marks of the IXw and VIIw, which is located in the immediate vicinity of residential and public buildings, experiences the greatest man-made load.

The rate of displacement of the retaining wall in the horizontal plane is 0.4–1.7 mm/year.

The rules of technical operation [29] set the following maximum permissible displacement values for the period of operation specifically for protective hydrotechnical structures of a vertical profile: average settlement – 400 mm, horizontal displacement of the top of the structure – 0 mm (not allowed).

Assuming that the retaining wall settles at the same rate throughout its lifetime, the actual average settlement does not exceed the specified tolerance. On the other hand, the detected horizontal displacements of the top of the vertical wall in profile indicate non-compliance with the established rules of technical operation.

The results of modeling displacements of the retaining wall in the horizontal plane (Fig. 8) reflect the presence of a tendency of steady displacement of the retaining wall in the direction of the Dnipro River. Horizontal displacements of the retaining wall exceed the regulatory tolerance [29]. At the same time, the values of the horizontal displacement vectors (Tables 6, 7) of most wall signs exceed the accuracy of determin-

Table 2

Indicators of accuracy of geodetic measurements of rectangular coordinates in the geodetic networks of Kremenchuk in 2018

Name of the point	MSE position of points, m		
	m_x	m_y	m_s
Igr	0.019	0.029	0.035
IIgr	0.018	0.028	0.033
IIIgr	0.017	0.030	0.034
IVgr	0.020	0.031	0.037
Vgr	0.024	0.029	0.038
Iw	0.027	0.027	0.038
IIw	0.028	0.024	0.037
IIIw	0.028	0.024	0.037
IVw	0.031	0.032	0.045
Vw	0.026	0.020	0.033
VIw	0.024	0.015	0.028
VIIw	0.024	0.015	0.028
VIIIw	0.018	0.009	0.020
IXw	0.018	0.008	0.020
VIgr	0.005	0.005	0.007
VIIgr	0.015	0.005	0.016
VIIIgr	0.006	0.005	0.008

Table 3

Marks and vertical displacements of wall signs

Name of the point	Results of levelling		Vertical displacement ΔH, mm (formula 4)
	1982	2000	
	Mark, m	Mark, m	
Igr	10.041	10.034	–7
IIgr	10.038	10.033	–5
IIIgr	10.090	10.078	–12
IVgr	10.227	10.213	–14
Vgr	9.416	9.411	–5
Iw	9.512	9.501	–11
IIw	9.428	9.426	–2
IIIw	9.469	9.464	–5
IVw	9.485	9.464	–21
Vw	9.480	9.458	–22
VIw	9.480	9.436	–44
VIIw	9.436	9.417	–19
VIIIw	9.398	9.368	–30
IXw	9.432	9.398	–34
VIgr	9.907	10.000	+93
VIIgr	10.618	10.334	–284
VIIIgr	10.463	10.272	–191

Table 4

Analysis of the results of geodetic measurements in the geodetic networks of Kremenchuk in 1982 and 2000

Name of the point	Results of linear-angular geodetic measurements (rectangular coordinates), m				Vectors of horizontal displacement along the axes, mm (formulas 1, 2)		Absolute horizontal vector displacement S, mm (formula 3)	Displacement Vector in space *f*, mm (formula 6)
	1982		2000					
	X	*Y*	*X*	*Y*	Δ*X*	Δ*Y*		
Igr	10.865	1,276.947	10.775	1,276.967	–90	-20	92	**92**
IIgr	15.155	1,159.927	15.085	1,159.897	–70	-30	76	**76**
IIIgr	0.185	1,010.167	0.095	1,010.147	–90	-20	92	**93**
IVgr	33.765	823.757	33.765	823.737	0	-20	20	**24**
Vgr	169.945	551.687	169.945	551.687	0	0	0	**0**
Iw	291.495	399.377	291.425	399.377	–70	0	70	**70**
IIw	439.235	332.057	439.175	332.047	–60	-10	61	**61**
IIIw	464.835	320.437	464.785	320.427	–50	-10	51	**51**
IVw	595.395	260.957	595.385	260.947	–10	-10	14	**25**
Vw	609.615	255.357	609.605	255.337	–10	-20	22	**31**
VIw	786.865	186.667	786.845	186.667	–20	0	20	**48**
VIIw	800.935	181.147	800.935	181,137	0	-10	10	**21**
VIIIw	971.725	114.927	971.695	114.927	–30	0	30	**42**
IXw	994.945	109.357	994.905	109.357	–40	0	40	**52**
VIgr	1,159.995	89.997	1,159.995	89.997	0	0	0	**93**
VIIgr	1,311.335	79.577	1,311.475	79.517	+140	-60	152	**322**
VIIIgr	1,479.015	52.987	1,479.025	52.987	+10	0	10	**191**

Table 6

Analysis of the results of linear-angular and satellite measurements in the geodetic networks in Kremenchuk in 1982 and 2018

Name of the point	Results of linear-angular geodetic measurements (rectangular coordinates), m				Vectors of horizontal displacement along the axes, mm (formulas 1, 2)		Absolute horizontal vector displacement S, mm (formula 3)	Displacement vector in space *f*, mm (formula 6)
	linear-angular measurements		satellite observations					
	1982		2018					
	X	*Y*	*X*	*Y*	Δ*X*	Δ*Y*		
Igr	10.865	1,276.947	10.769	1,276.883	–96	–64	115	**115**
IIgr	15.155	1,159.927	15.075	1,159.820	–80	–107	134	**134**
IIIgr	0.185	1,010.167	0.097	1,010.077	–88	–90	126	**127**
IVgr	33.765	823.757	33.765	823.651	0	–106	106	**107**
Vgr	169.945	551.687	169.960	551.633	+15	–54	56	**56**
Iw	291.495	399.377	291.423	399.342	–72	–35	80	**81**
IIw	439.235	332.057	439.179	332.019	–56	–38	68	**68**
IIIw	464.835	320.437	464.783	320.400	–52	–37	64	**64**
IVw	595.395	260.957	595.382	260.921	–13	–36	38	**43**
Vw	609.615	255.357	609.602	255.319	–13	–38	40	**46**
VIw	786.865	186.667	786.852	186.657	–13	–10	16	**47**
VIIw	800.935	181.147	800.937	181.121	+2	–26	26	**32**
VIIIw	971.725	114.927	971.704	114.914	–21	–13	25	**39**
IXw	994.945	109.357	994.913	109.345	–32	–12	34	**48**
VIgr	1,159.995	89.997	1,160.000	90.000	+5	+3	3	**93**
VIIgr	1,311.335	79.577	1,311.473	79.512	+138	–65	153	**323**
VIIIgr	1,479.015	52.987	1,479.017	52.988	+2	+1	2	**191**

ing the coordinates (Table 2). The retaining wall itself has been functioning for decades. All this testifies to the admissibility of the assumption regarding the need to carry out geodetic monitoring in full to predict the behavior of the retaining wall.

Discussions. Taking into account the fact that the displacement of the retaining wall of Kremenchuk embankment occurs slowly, a more reliable picture of the displacements will be shown by relatively high-precision observations. In this case, there is no need for frequent observations. At the same time, intensive use of the park for recreation, tiled pavement, trees, bushes and other conditions of recreational areas limit the possibilities of choosing schemes, methods and techniques for carrying out geodetic monitoring of the retaining wall. Therefore, the task of designing a special geodetic network for monitoring plan-height displacement of the retaining wall of the embankment of Kremenchuk should also include:

- the selection among the existing points of the geodetic network of the city of Kremenchuk of reference points that can serve as starting points for observations by linear-angular methods and leveling, taking into account the reliability and

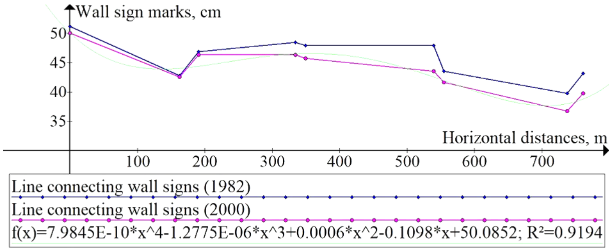

Fig. 5. Retaining wall subsidence model

stability of the position, the location outside the deformation zones, the conditions of visibility and the ease of binding to them, minimization of time expenditure;

- substantiation of the optimal distance between working wall marks (for example, in scientific studies, benchmarks and deformation marks on retaining walls are placed at different distances: 15–20 [2] or 20–50 m [15]);
- selection of the best location of working wall signs on the retaining wall, taking into account visibility conditions and ensuring the convenience of performing geodetic observations by linear-angular methods, leveling and GNSS;
- choosing the design of working wall signs for monitoring horizontal and vertical displacements, taking into account the material of the retaining wall;
- selection of the location of auxiliary (connecting) points to ensure the possibility of direct observation of the retaining wall by linear and angular methods and leveling, taking into account the existing situation and convenience of observations;
- selection of the construction of temporary signs for securing auxiliary points.

A methodology for the analysis of geodetic measurements of past years has been developed for the needs of geodetic monitoring of retaining walls, which was tested on the example of the retaining wall of Kremenchuk embankment. As evidenced by the results of measurements obtained in past years in the geodetic networks of the city of Kremenchuk, a reliable analysis of the spatial displacements of retaining walls to identify local processes and assess their reliability and stability is also necessary during their operation. Prospects for the development of research are geodetic monitoring of the research object according to the developed technological scheme (Fig. 1). Neglecting

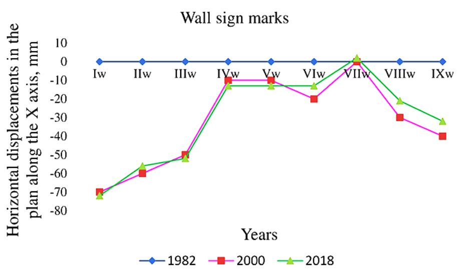

Fig. 6. Scheme of planned displacements of wall signs along the X axis

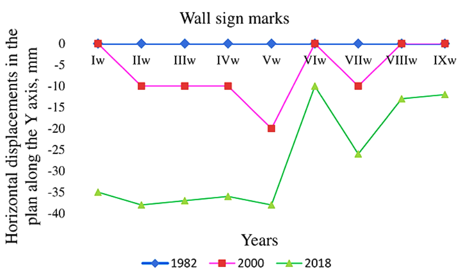

Fig. 7. Scheme of planned displacements of wall signs along the Y axis

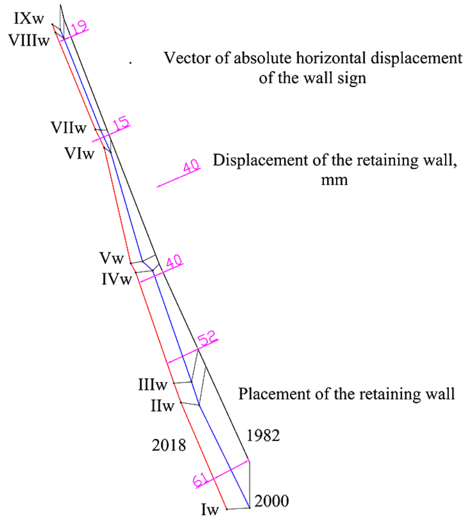

Fig. 8. The model of the displacement of the retaining wall in the horizontal plane

monitoring can lead to unpredictable consequences over time. Further research should be directed to the substantiation of the forecast models of future changes through the combined analysis of previous and modern results of geodetic measurements, geospatial information that will be needed [30, 31] and possibilities of use of remote technologies [32].

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Обґрунтування методології геодезичного моніторингу підпірних стін на прикладі набережної міста Кременчук

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Мета. Розроблення методики аналізу результатів геодезичних вимірювань, за яких можливим є використання матеріалів минулих років для потреб геодезичного моніторингу на прикладі підпірної стіни в умовах рекреаційних територій міста.

Методика. Розроблена технологічна схема геодезичного моніторингу підпірних стін із виділенням чотирьох основних етапів: аналізу вихідних даних, проєктування геодезичного моніторингу, проведення періодичних спостережень, опрацювання та аналізу результатів геодезичного моніторингу. Умови рекреаційних територій міста визначають особливості геодезичного моніторингу, обмежують можливості вибору схеми геодезичної мережі, методів і методики вимірювань. У зв’язку з цим запропоновано розробляти моделі розвитку деформаційних процесів уже на першому етапі геодезичного моніторингу, що дозволить у подальшому здійснювати геодезичний моніторинг з більшою достовірністю та уникати можливих помилок прогнозування.

Результати. Результати аналізу геодезичних вимірювань у геодезичних мережах згущення м. Кременчук (координат і позначок стінних знаків) показують наявність горизонтальних і вертикальних зміщень підпірної стіни. У горизонтальній площині підпірна стіна змістилася в південно-західному напрямку, у бік р. Дніпро. У вертикальній площині відбулося осідання підпірної стіни. Зміщення різних частин підпірної стіни нерівномірні. При цьому середньорічна швидкість як горизонтальних, так і вертикальних зміщень рівнозначна та приблизно становить 1 мм/рік. Значення векторів абсолютних зміщень стінних знаків у горизонтальній площині перевищують точність проведених геодезичних вимірювань і нормативні допуски.

Наукова новизна. Моделювання зміщень підпірних стін в умовах рекреаційних територій міста вже ведеться з урахуванням аналізу результатів геодезичних вимірювань минулих років.

Практична значимість. Дані аналізу результатів геодезичних вимірювань, проведених у геодезичних мережах згущення м. Кременчук, свідчать про наявність деформаційних процесів і обґрунтовують необхідність у їх контролі через проведення геодезичного моніторингу. Запропоновані моделі можуть бути використані як порівняльний і комбінований аналіз майбутніх прогнозних змін на основі попередніх і сучасних результатів вимірювань, що є темою для окремого дослідження.

Ключові слова: *геодезичний моніторинг, підпірна стіна, стінний знак*

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