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PREDICTING OF VERTICAL DISPLACEMENTS OF STRUCTURES OF ENGINEERING BUILDINGS AND FACILITIES

Purpose. The research is aimed at solving the tasks of monitoring and assessing the state of an engineering object and determining predictive characteristics in the form of construction of various models of settlement and deformation of a structure based on the results of geodetic measurements, taking into account the space-time interaction of engineering objects with the geological environment in a seismic zone with the earthquake energy class values of $K = 6–7.5$, in the area of possible underground fluctuations with an intensity of 3–4 points.

Methodology. An analytical methodology has been developed that takes into account the geological conditions of the foundation, changes in the groundwater level, soil compaction under significant static load, as well as the accumulation of damage in the supporting structures caused by the impact of numerous and insignificant underground seismic shocks, for predicting the vertical displacements of the engineering facility supporting structures. To assess the durability and stability of design components, the least squares method is used, which makes it possible to display the patterns of deformation process development. Obtaining new results during the period of further operation in order to draw up a technical conclusion on the state of the facility and its stability is possible by monitoring and predicting deformation deviations of individual components of an engineering object in the vertical plane.

Findings. With the help of mathematical modeling of strength calculations of supporting structures based on geodetic measurement data, it is possible to determine the quantitative characteristics and patterns of deformation process development during the engineering facility operation. The performed calculations on mathematical modeling make it possible to reveal the distribution of the parameters of amplitude-frequency characteristics of the linearly deformable monolithic plate upper layer along the perimeter and to predict possible deformation changes over a certain period of time during the engineering facility operation. According to the executive survey data, vertical deviations of structures along the facility perimeter *AB, BC, CD, DA* have been determined in the range from 1 to 27 mm, which is the basis for predicting deformation deviations in the vertical plane. In addition, as a result of engineering-geological surveys conducted on the building construction site, the geological-lithological structure of the site has been determined.

Originality. A methodology for predicting the deformation processes of individual sections of vertical structures and monolithic walls of an engineering facility, which are associated with the complex lithological structure of the foundation section and the location of the object in a seismically hazardous zone, is proposed.

Practical value. The obtained results of studying the deformation processes of structures and individual facilities make it possible to take into account the form of complex interaction of individual sections and, in general, to predict deformation deviations in the vertical plane.

Keywords: *engineering facilities, deformation processes, geomechanical assessment, seismic zone, geodetic monitoring*

Introduction. Prediction of vertical displacements of structures of engineering buildings and facilities is an important problem in engineering construction, since deformations can lead to serious consequences, such as destruction of structures, deterioration of their reliability and safety. One of the main causes of vertical displacements is the heterogeneity of the soil foundation on which the building is located [1]. Under the influence of external loads, for example, when soil moisture changes or seismic vibrations occur, the soil can change its physical properties, which can lead to heterogeneous load on building structures and deformations [2]. Another cause of vertical displacements may be improper design or errors during construction process, such as heterogeneous soil compaction or improper positioning of supporting walls [3].

Various methods such as numerical modeling, displacement measurement and optical sensors are used to predict vertical displacements of engineering buildings and facilities. In addition, it is important to conduct regular inspections of buildings and facilities in order to identify and correct possible problems before they lead to serious consequences. However, predicting vertical displacements of structures of engineering buildings and facilities is a complex task that requires consideration of of many factors, such as geological-climatic conditions, construction conditions, design peculiarities, etc. Therefore, it is necessary to carefully study each specific case and make individual decisions for each object [4, 5].

The development of technologies for performing mine surveying and geodetic monitoring observations of industrial objects and engineering facilities has made it possible to scientifically substantiate and quickly assess changes in their geomechanical state; to predict horizontal and vertical displacements of engineering facilities during the construction of underground structures in densely built-up populated areas, displacement of the earth's surface in the form of trough formation and collapse of the mine working roof, surface facilities (towers, pithead buildings, processing plants, etc.) at mining enterprises; and, on the basis of the information obtained, take timely reliable, precautionary and protective measures to prevent dangerous technogenic phenomena and situations in seismically hazardous zones [6]. Given the different geological peculiarities of the foundation soils of engineering facilities, possible seismic vibrations, and due to the limited land areas and their high cost, industrial safety of engineering objects is required for their long-term preservation and operation.

Intensive construction during the erection of engineering facilities requires constant geodetic monitoring and special control over their stability and preservation of the initial (design) position for a long period of operation and service life. For this purpose, technologies for 3D-modeling of buildings and facilities based on the results of scanning and aerial photography obtained from UAVs are currently developing dynamically [7, 8]. Geodetic monitoring using high-precision electronic devices and methods for measuring deformation changes in the operation of building objects for various purposes, taking into account various conditions of their location, is considered to be one of the many methods of special observations [9].

Numerous studies on the deformation characteristics of engineering buildings and industrial objects (mines, open-pits, underground and hydraulic structures, railway bridges and highways, etc.) have contributed to the timely adoption of special measures and to maintaining the safety of their operation. At the same time, it is particularly important to conduct geodetic measurements in conjunction with data from automated surveillance systems (sensors, tiltmeters, scanners) for industrial objects and engineering facilities in order to determine numerous factors, affecting their long-term stability and safety in various difficult conditions [10, 11].

The study object is located in the foothill area of the Zaili Alatau, and geodetic observations of deformation processes are performed under various dynamic loads, taking into account seismic effects. The main task of our geodetic observations is to determine significant natural and technogenic factors affecting the operational safety of an engineering facility located on the territory of the seismic zone, with the earthquake energy class values of $K = 6–7.5$ in the area of possible underground fluctuations with an intensity of 3–4 points (Fig. 1) [4–6].

The relief of the earth›s surface within the study object has a gentle-sloping character with a general slope in the north direction. The absolute marks for the site are in the range of 899.16–915.33 m.

This region climatic conditions are characterized by negative air temperatures up to –25 degrees in winter and hot summers up to 40 degrees with increased intensity of solar radiation. This makes it necessary to protect buildings from the cold in winter and from excessive overheating in the hot season [12].

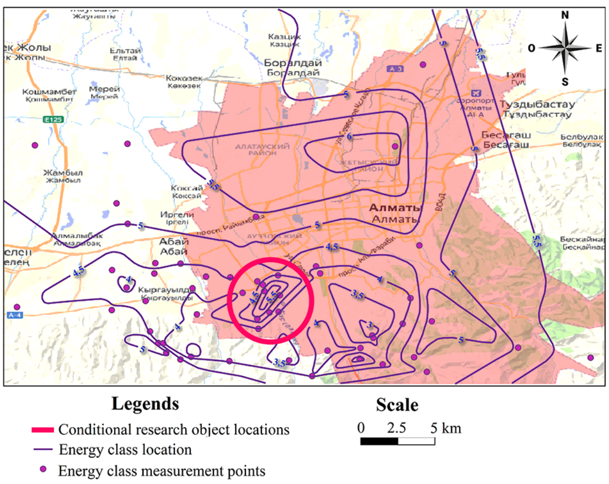

Fig. 1. Map of isolines of the earthquake energy class, Almaty

When planning the construction of industrial objects and engineering facilities, special geological studies are performed in order to avoid various types of errors in calculating the foundation section of an object under construction [13]. When designing and building of mining, hydrotechnical and other industrial facilities, engineering-geological surveys are initially performed for making managerial decisions on choosing the type of foundation, its depth and options for strengthening the foundation and its stability. The geological-lithological table includes a characteristic of topographical relief, physical-geological processes, hydrological conditions, physical-mechanical properties of soils, as well as other materials and predictions [14].

As a result of engineering-geological surveys conducted on the construction site of the engineering building, the geological-lithological structure of the site has been determined. The structure includes alluvial-proluvial deposits of the Upper Quaternary age (apQIII), represented by subsiding loams and a thick stratum of pebble soils with sand filler with up to 30 % boulders (Table 1).

The standard soil freezing depth is: 0.92 m – for loam; 1.36 m – for bulk and pebbly soils. According to the content of sulphates and the degree of hazardous impact of soils on concrete and reinforced-concrete material of design components, the soils are non-aggressive. By the chloride content, the soils are non-aggressive. By the total salt content, the soils are non-saline.

The issues of performing geodetic observations of the deformations of buildings under the conditions of possible earth›s surface seismic vibrations and the complexity of the geological structure include the problems of continuous monitoring and accuracy of measuring design parameters. The factors significantly affecting the stability of an industrial and administrative building are natural and technogenic factors revealed during special observations using high-precision geodetic measurements, type A settlement deformation marks, digital tilt recorders, seismic monitoring systems, as well as other modern devices and technologies [15].

During the operation of an industrial object and additional engineering facilities, due to a change in the level of groundwater, filling or flooding of technical floors, compaction of the foundation soil due to previously unaccounted for physical-mechanical rock properties are possible. In addition, there are other factors that cannot always be additionally determined as a result of geodetic observations during the operation period [16]. Experience shows that many additional factors can be identified during periodic monitoring of their deformations, taking into account the specific conditions of the research object location and the geomorphological peculiarities of the research object territory [17]. The unresolved problems include issues of interacting soil foundation of the structure, geodynamic processes and the external environment near the foothill area with periodic insignificant earth›s surface seismic vibrations [18]. The accumulation of damage in the supporting structures of the building during

Table 1

Structure of the site geological section

No	Soil type	Description of rocks	Thickness, m
1	Topsoil	With plant roots	0.2–0.3
2	Compacted bulk soil	Loam, pebble, sand	0.8
3	Hard loam macroporous, subsiding	With rare inclusions of fine pebbles	0.7–1.2
4	Pebble soil	With sand filler with boulders up to 30 %	3.5–4.0

operation in the conditions of seismically hazardous areas can lead to possible changes in the dynamic characteristics of the building that have not been determined by geodetic monitoring [19].

Given the peculiarities of the location of engineering buildings and facilities on industrial sites, the factors affecting their stability during operation, as well as factors that have been little studied in the development of a construction project, require constant geodetic control, which is regulated by normative legal documents and materials.

Research Methods. There are several methods for studying the problem of predicting vertical displacements of structures of engineering buildings and facilities. The main one refers to geodetic measurements. This method is based on the use of geodetic equipment for determining the vertical deviations of structures. With this method it is possible to obtain accurate data on vertical deviations of structures in a particular section of a building or facility.

The use of mathematical models involves the construction of mathematical models based on the study of properties and characteristics of structures. These models can be used to predict vertical displacements of structures based on various factors such as a load on building, geological conditions, and other factors. Methods of non-destructive testing, which are based on the use of various devices and technologies that allow determining the characteristics of structures without violating their integrity, can be used to reveal hidden defects and damage to structures that may cause vertical displacements.

Methods of computer modeling, which are based on the use of computer programs to create 3D-models of structures and predict their behavior in different conditions, can be used to analyze different variants of loading on structures and predict their behavior in different scenarios.

Various devices are used for special observations, such as a Leica TS03°5″ R500 electronic tacheometer with a measurement accuracy of up to 1 mm, special settlement deformation marks and seismic monitoring systems, digital data recorders and highly sensitive geodetic measurement sensors. The tacheometer is ideal for operations that require medium measurement accuracy: ideal for land surveying and construction, making it easy to do near offset and survey. It provides an optimal balance of range, accuracy, reliability, beam visibility, laser spot size, measurement time, and high dust and moisture protection degree.

To perform measurements on a vertical monolithic plate, type *A* deformation marks are set, designed to monitor settlement of brick and reinforced-concrete structures. Deformation marks are set at a height of approximately 0.3–0.6 m from the floor and should be available for geodetic operations (high-precision leveling). To ensure long-term operation, the marks have a number applied with indelible paint and a special cap to protect against damage. For further measurements, the location of each mark is indicated in the object plan.

Type *A* settlement deformation marks with parameters $l = 10$ cm are mounted into the wall thickness to a depth of 8 cm on the joints in the lower part of the wall for systematic control of deformation processes. For the validity of the results of the deviation values, the marks are set taking into account the individual structure peculiarities, which are revealed in the process of studying the building parameters [20].

The horizontal displacements of the deformation signs are measured with the methods of axial observations of certain directions by a polar way using an electronic tacheometer. The method of axial observations is performed during certain periods of measuring the deformation mark deviations on the engineering building from the reference line matching the structure axis [21].

The axial observations make it possible to determine the direction of shear in the horizontal plane. No deviations in the horizontal plane from the reference line *AB, BC, CD, DA* of the engineering facility are detected. All geodetic observations are performed in compliance with building codes and regulations.

Executive survey is performed for geodetic control and is the result of measurements with an electronic tacheometer. It is known that geodetic observations of deformations of buildings and individual structures are an unrelated and unsystematic quantitative data set reflecting the interaction of volume-panel structures with the soil foundation and the external environment [22].

In the area of an engineering facility construction, special attention is paid to the values of horizontal and vertical dynamic loads, taking into account the physical-mechanical properties of the foundation and the use of steel trusses and reinforced-concrete beams, special coatings in the form of ST N135-930 corrugated steel deck and clay-concrete wall panels. However, during the erection of facilities in this area, changes in the groundwater level, the foundation soil compaction under significant load, accumulation of damage in load-bearing structures under conditions of multiple impact of weak but significant underground shocks, as well as changes in stiffness characteristics due to numerous redevelopments of premises are not taken into account.

The deformations of an engineering building and its individual structures are predicted by various methods involving the theory of probability and mathematical statistics. As a result of geodetic measurement processing, the root-mean-square errors of vertical displacements have been obtained, which correspond to the values of the second class of accuracy for determining the deformation characteristics of buildings with sandy and clay soils in the foundation. The height of the deformation mark is calculated by the formula

$$H_i = H_S + h_{S-I} = H_S + D_{S-i} \cdot \cos Z_{S-i},$$

where H_S is station elevation mark *S*; h_{S-i} is the difference of elevation marks between a station and settlement mark; D_{S-i} is distance from the station to the settlement mark; Z_{S-i} is angular distance measured from the normal to the settlement mark.

Results and Discussion. According to geodetic measurement data along the entire perimeter of the engineering building on settlement marks in accordance with the observation schedule (March, June, September, December), vertical deviations ranging from 1–27 mm have been determined. As a result of the analysis of the made measurements, a scheme of the executive survey of vertical structures of monolithic plates with the deviation values along the *AB, BC, CD, DA* line is presented (Fig. 2).

Table 2 presents the results of observations on the characteristic points of the wall top and on type A settlement deformation marks, as well as revealed vertical deviations of the main monolithic structures of the building. In this case, the geological-lithological structure of the site is taken into account in the form of alluvial-proluvial deposits of the Upper Quaternary age, represented by subsiding loams and a thick layer of pebble soils with sand filler and boulders on the territory of the monitored engineering facility. These factors of the geological-lithological structure significantly influence on the geodynamic processes in the study area, including vertical and horizontal deformations of engineering structures, and therefore it is important to consider them when developing design solutions for the construction of facilities in this area. In addition, subsiding loams and pebble soils with boulders are typical soils for this region, and can contribute significantly to the formation of geotechnical characteristics and parameters, such as the internal friction angle, soil cohesion and drainage, which should also be taken into account when designing and operating engineering facilities.

Line *AB* in Fig. 3 illustrates the amplitude-frequency characteristic of the monolithic plate upper layer, which can be exposed to linear deformation. This is important informa-

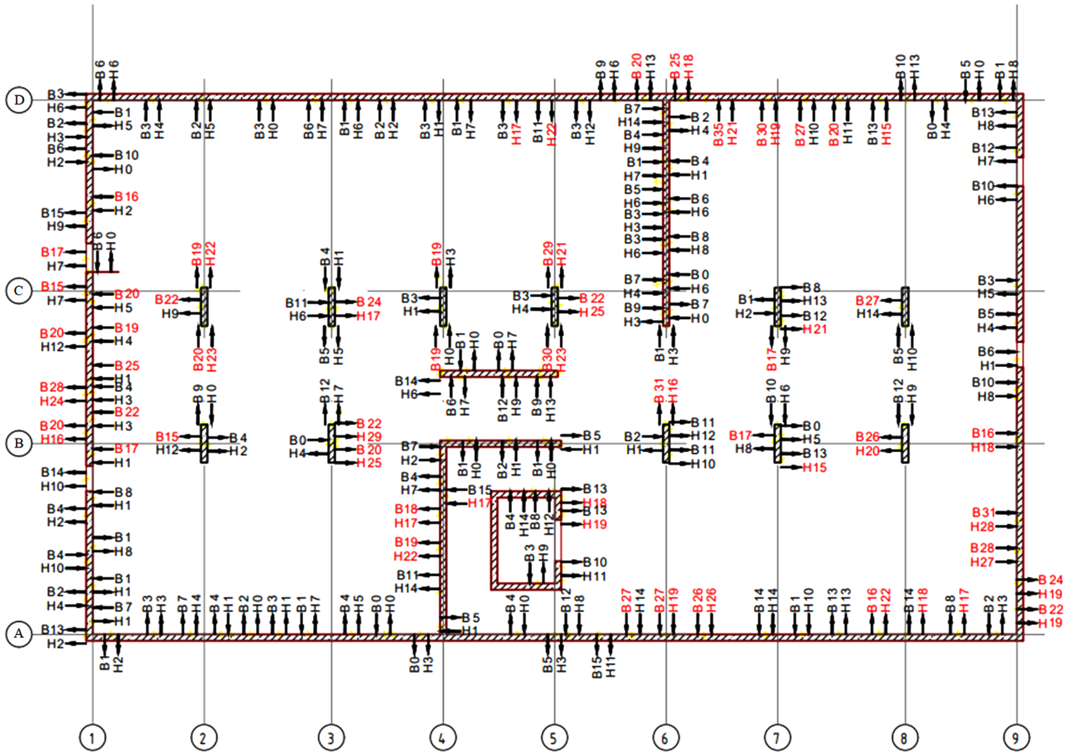

Fig. 2. Scheme of executive survey of displacement of vertical structures of monolithic plates based on geodetic observation data:
A–D – building axis along the x-axis; 1–9 – building axis along the y-axis; B – wall top; H – wall bottom; Red – deviations exceeding permissible values

Table 2

Main monolithic-block structures of an engineering facility and deviations from the vertical

Distance from the joint of vertical structures, m	Deviation, mm
0.6	1
1.9	3
3.1	7
4	4
4.9	2
5.9	3
6.8	1
8.1	4
9.2	0
10.3	0
13.3	4
14.5	5
14.9	12
15.9	15
16.9	27
18	27
19.2	26
21.1	14
22.3	1
23.4	13
24.7	16
25.5	14
27.2	8
28.4	2

tion for assessing the behavior of the structure under various loads, as well as for determining its stability and durability during operation. In addition, based on the data presented in Fig. 3, it is possible to calculate and predict the deformation characteristics of the plate upper layer, which makes it possible to make managerial decisions on its further operation and repair.

The amplitude-frequency characteristics of the linearly deformable upper layer of a monolithic plate show the dependence of the fluctuation amplitude on the vibration frequency. These characteristics can be used to determine the dynamic properties of the plate upper layer material, such as stiffness and damping. They can also be used to assess possible structural damage caused by vibrations, for example when passing vehicles near a building. In addition, the amplitude-frequency characteristics can be used to optimize the design of a building or facility in order to improve its dynamic properties.

The obtained patterns for predicting deformation devia-

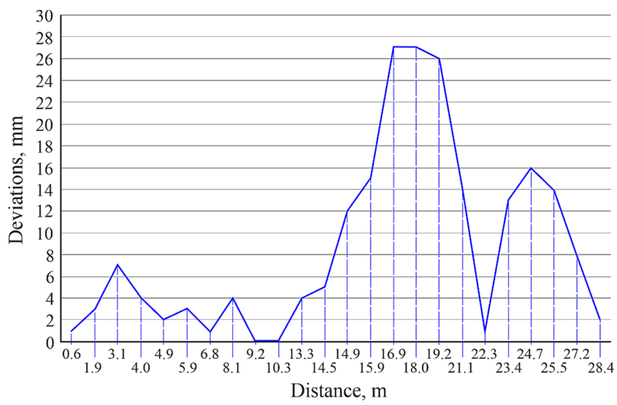

Fig. 3. Amplitude-frequency characteristic of a linear-deformable upper layer of a monolithic plate

tions, taking into account possible changes during the service life of a building, make it possible to identify indirect characteristics of deformations (spatial stiffness of the structure foundation, elasticity and plasticity of wall materials) and using geodetic marks set at control points to determine the probability-statistical characteristics of the difference of settlement values of symmetrical monitored marks.

The main purpose of geodetic monitoring is the timely detection of dangerous deformation values, determination of the causes of their occurrence, predicting of the dynamics and patterns of displacement development, as well as providing measures to prevent critical situations. In geodetic practice, predicting has become an integral part in solving complex issues of geodetic monitoring results. Based on the systematic processing of the initial data, the results of accumulative instrumental observations and engineering-geological surveys, a comprehensive analysis of the shear deformation parameters of all design components of the structure and the geodynamic characteristics of the soil foundation is performed. An actual problem when performing geodetic operations is the determining of patterns of development of deformation processes and methods for their prediction when making managerial decisions to ensure the engineering facility safe operation. Managerial decisions for the problems of geodetic monitoring of engineering facilities and analysis of their displacements are the most difficult due to the high requirements for measurement accuracy, the need to develop automated technical observation means and flexible tools for processing and analyzing data, and the use of precision geodetic devices.

The results of geodetic measurements at all stages of construction and operation of building objects are used as the basis for creating an integrated system for assessing and predicting the main characteristics of the dynamics of the development of the engineering facility deformation processes. The solution of monitoring tasks requires a comprehensive assessment of the qualitative state for the entire period of construction, operation and liquidation of industrial buildings and engineering facilities. Based on the results of geodetic measurements, taking into account geological-geophysical data of soil foundations, as well as climatic conditions, tectonic disturbances and other factors of the earth's surface, predictive characteristics are determined in the form of constructing various digital two- and three-dimensional models of engineering facility deformation displacements.

Determination of tendencies in the deformation process development is possible only by using the entire complex of data, complete and comprehensive information on the state of engineering facility and its displacements based on modeling, the method of statistical extrapolation, in which an approximating function is selected with account of the conditions and limitations of the controlled deformation process development. Thus, a statistical pattern is formed from strictly defined single phenomena, with the help of which reliable predictions can be obtained by mathematical means.

The tasks of studying the issues of the deformation state of industrial buildings and engineering facilities are very relevant due to the technologically complex processes performed. For determining patterns of deformation displacement manifestation, modern tools of monitoring (electronic tacheometers, laser levelers, special automated sensors, etc.), electronic computers, and mathematical modeling based on reliable initial observational data are widely used in scientific research and during the operation of building objects for any purpose.

This makes it possible to determine changes in the vertical position characteristics of the settlement marks on the joints of the engineering facility supporting structures. The authors of the paper have developed an analytical methodology for predicting displacements in individual sections of the facility perimeter based on the factors influencing the change in vertical settlement accumulations in supporting structures under conditions of multiple impacts of weak but significant underground shocks. The proposed formulas allow for predicting.

1. Linear regression

$$h = 0.458l + 2.222.$$

2. Quadratic regression

$$h = -0.046l^2 + 1.783l - 4.010.$$

3. Cubic regression

$$h = -0.009l^3 + 0.327l^2 - 2.597l + 6.87,$$

where h is the measurement of the vertical deviation of the deformation mark on the wall relative to the reference line (section line), mm; l is the length of certain facility wall sections, on which observations are conducted, m.

The proposed methodology for predicting deformations is based on the correlation theory of random functions, taking into account the conditions for the homogeneity of modeled implementations. Compliance with the homogeneity of functions makes it possible to assess the parameters of the predictive kinematic and dynamic models using two main parameters and deformation characteristics for the prediction with a pre-calculation of their accuracy.

By assessing the statistical homogeneity of the geodetic measurement results during different observation periods, using the criterion of stochastic changes in the possible settlement of the foundation and the body of the structure along the perimeter, it is possible to optimally assess the deformation processes in different sections of the foundation plate according to settlement marks.

Further research into the problem of predicting vertical displacements of structures of engineering buildings and facilities can be directed to various aspects of this problem. More detailed point studies of the influence of various factors, such as geological, geomorphological, hydrological, climatic, etc., on the vertical displacements of structures are important; development of new methods and technologies for predicting vertical displacements that are more accurate, reliable and cost-effective; assessing the effectiveness of different methods for predicting vertical displacements of structures, as well as comparing existing methods and technologies; studying the influence of new building materials and technologies on vertical displacements of structures, as well as the development of methods and technologies to reduce their influence; development of new methods for monitoring and controlling vertical displacements of structures that are more efficient and cost-effective.

All these research areas are of great importance for improving the efficiency and reliability of predicting vertical displacements of structures of engineering buildings and facilities, which in turn contributes to ensuring the safety and stability of such objects in different conditions.

Conclusions. Based on the data of the executive survey of monolithic-block structures of an engineering facility, displacements in the vertical plane with values from 1 to 27 mm have been identified. Mathematical operations with the initial modeling data make it possible to reveal the distribution of the parameters of amplitude-frequency characteristics of the linearly deformed monolithic plate upper layer along the perimeter, which is the basis for predicting deformation deviations in the vertical plane over a certain period of time during the engineering facility operation.

Based on this, an analytical methodology for predicting vertical displacements of volume-panel structures using a probabilistic-statistical method is proposed. The proposed methodology for predicting the technical state of an engineering facility is implemented at various stages, namely, design, construction and operation of an engineering facility. The presented methodology for predicting deformation deviations of building components and structures allows making managerial decisions regarding control geodetic observations, which are necessary to ensure long-term and safe operation of industrial facilities, as well as to ensure their stability.

Further geodetic observations of possible settlements are required, taking into account possible changes during the service life of facilities and buildings associated with the engineering-geological conditions of the foundation and location of the object in a seismically hazardous zone. The principle of predicting the state of engineering and industrial buildings is aimed at monitoring the technical state during operation and timely warning about changes in the conditions of homogeneity of the modeled implementations and taking measures to preserve and ensure their safety.

The research results can be used to predict the state of engineering facilities located in the foothill area with possible underground vibrations and tectonic faults.

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Прогнозування вертикальних зсувів конструкцій інженерних будівель та споруд

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Мета. Робота спрямована на вирішення завдань моніторингу та оцінки стану інженерного об'єкта й визначення прогнозних характеристик у вигляді побудови різних моделей осадки та деформації споруди за результатами геодезичних вимірювань з урахуванням просторово-часової взаємодії інженерних об'єктів з геологічним середовищем у сейсмічній зоні зі значеннями енергетичного класу землетрусу $K = 6–7.5$ у районі можливих підземних коливань інтенсивністю 3–4 бали.

Методика. Розроблена аналітична методика, що враховує геологічні умови основи, зміну рівня ґрунтових вод, ущільнення ґрунту під значним статичним навантаженням, а також накопичення пошкоджень у несучих конструкціях, спричинених впливом численних і незна-

чних підземних сейсмічних поштовхів, для прогнозування вертикальних зсувів несучих конструкцій. Для оцінки міцності та стійкості конструктивних елементів використано метод найменших квадратів, що дозволяє відображати закономірності розвитку деформаційних процесів. Спостереження та прогнозування деформаційних відхилень окремих елементів інженерного об'єкта у вертикальній площині дозволяє отримати нові результати в період подальшої експлуатації для складання технічного висновку про стан об'єкта та його стійкість.

Результати. Математичне моделювання розрахунків на міцність несучих конструкцій за даними геодезичних вимірювань дозволило визначити кількісні характеристики й закономірності розвитку деформаційних процесів при експлуатації інженерної споруди. Виконані розрахунки з математичного моделювання дозволили встановити розподіл параметрів амплітудно-частотних характеристик лінійно-деформованого верхнього шару монолітної плити по периметру та прогнозувати можливі деформаційні зміни протягом певного періоду експлуатації інженерної споруди. За даними зйомки були встановлені вертикальні відхилення конструкцій по периметру споруди *AB*, *BC, CD, DA* величиною від 1 до 27 мм, що стало основою прогнозування деформаційних відхилень у вертикальній площині. Крім того, на території будівництва будівлі були проведені інженерно-геологічні дослідження, внаслідок чого була встановлена геолого-літологічна будова ділянки.

Наукова новизна. Запропонована методика прогнозування деформаційних процесів окремих ділянок вертикальних конструкцій і монолітних стін інженерної споруди, пов'язаних зі складною літологічною будовою ділянки основи й розташуванням об'єкта в сейсмонебезпечній зоні.

Практична значимість. Отримані результати дослідження деформаційних процесів споруд і окремих конструкцій дозволяють ураховувати форму складної взаємодії окремих ділянок і загалом прогнозувати деформаційні відхилення у вертикальній площині.

Ключові слова: *інженерні споруди, деформаційні процеси, геомеханічна оцінка, сейсмічна зона, геодезичні спостереження*

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