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THE GEODETIC NETWORK ANALYSIS, PREREQUISITES AND FACTORS OF THE NEED FOR GEODETIC MONITORING OF SETTLEMENTS AND STRUCTURES DEFORMATIONS

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Abstract

The purpose of this article is to analyse the geodetic network, prerequisites and factors that arise for geodetic settlements monitoring and deformations of the ChNPP engineering structures. It is determined that one of modern applied geodesy directions is deformation monitoring. It consists in regular monitoring of buildings deformations and other important structures by geodetic methods, carried out with the aim of timely detection and prevention of emergency situations. The factors influencing the emergence of new tasks and changes in the construction situation at the shelter facility, which necessitated the reconstruction of the planned and height geodetic network, are analysed. The necessity of organising observations of new control marks in the western part of the shelter is established. The influence of external factors that cause structural changes to the foundation under the building, the outer parts of the brick walls and man-made factors, the mechanism and intensity of these processes were analysed. The optimum height of sedimentary marks from the level of the blind area is determined. The list of objects for monitoring and observation of the building structures of the shelter was determined. The scheme of the main planned reference geodetic network at the facility and ensuring the required accuracy of deformation measurements was developed. The long-term control leveling of the height network of the investigated object shows that its reps, especially the deep and fundamental ones, are stable and can be used for further observations of vertical structures deformations. Thus, to ensure proper accuracy of leveling control marks of buildings and structures of the shelter complex, the height network of deep and fundamental references should be such that the distance between them does not exceed 0.5 km. The tolerance for the accuracy of subsidence determination of the marks of the upper shelter levels, which can be determined only by remote method, for example, trigonometric leveling, should be taken as for the II class of measurement accuracy, not more than 2 mm.

Key words: deformation monitoring, geodetic reference network, subsidence marks, depth and foundation raps.

Introduction

One of modern applied geodesy directions is deformation monitoring. This concept includes geodetic monitoring of settlements and deformations of foundations, as well as other important structural elements of buildings and structures. In addition to them, the objects of deformation monitoring can be foundations, structures of buildings or their parts, new construction objects, engineering networks, underground structures and infrastructure facilities surrounding them (Celms et. al., 2022; Яковенко and Нестеренко, 2019).

Deformation geodetic monitoring involves regular monitoring of deformations of buildings and other important structures using geodetic methods, and is carried out to detect and prevent the development of emergencies in a timely manner. This type of engineering monitoring is an important link in construction, as well as in the system of state and departmental technical supervision (Sztubecki et. al., 2022; Vynohradenko et. al., 2023).

Monitoring of building structures is carried out on the basis of an approved programme using technical means of non-destructive testing and the frequency established in the programme. The frequency of work is determined taking into account the responsibility classes of building structures, according to Building code DBN B.1.2-14:2018 (ДБН, 2019). The minimum frequency of observations is set according to the design and regulatory documents or special requirements for a particular facility. If necessary, the frequency of certain types of observations of building structure elements and the construction object may be adjusted.

Continuous monitoring of the technical condition of buildings and structures using automated systems is organized on structures that are responsible for safety criteria. In this case, devices and equipment

with automatic storage, processing and transmission of measurement results via information communication channels are used (Третяк and Савчин, 2013; Могильний et. al., 2010).
Limit parameters values of construction objects are assessed according to the criteria for the condition of buildings and structures elements, which determine under what conditions it is impossible for them to perform their functions for technical reasons, which include the risk of destruction of individual elements, loss of overall stability, etc. Assessment of technical condition parameters according to their limit criteria is used to make decisions on:

- ensuring people's safety;
- transfer of the facility to emergency operation, implementation of emergency measures and minimisation of possible consequences;
- bearing structures strengthening of the facility.

Analyzing the causes of structures deformation, it can be argued that man-made factors have the greatest impact. They are the most dangerous, as the creation of artificial reservoirs not only floods hundreds of thousands of hectares of land, but also disrupts the water balance of the planet as a whole. Such human activity leads to changes in riverbeds, which in turn cause endogenous and exogenous phenomena that lead to emergencies, so it is necessary to monitor the condition of engineering structures located in close proximity to reservoirs (Смолій, 2015; Войтенко et. al., 2009).
Having considered the causes of engineering structures deformation, their measurements can be divided into two independent groups (Суярко et. al., 2019). The first group includes: studies of the physical and mechanical properties of the foundation soils, pressure measurements under the foundation sole, measurements of the foundation temperature, groundwater level fluctuations, etc. All these types of measurements can be united under the common name of "physical and mechanical supervision". The second group includes measurements of settlements and deformations of structures. These measurements are carried out both by classical geodetic and other methods. It is clear that the measurement results of these two groups should be considered comprehensively.

Methodology of research and materials

The plan-height position of the northern and southern foundations of the service area of the new safe confinement of the ChNPP is monitored by observing control marks installed on the structures of the outer wall of the hinged supports gallery, which rest directly on the grillage and are structurally connected to them. The marks are installed in increments of about 20 m, taking into account the location of the thermal joints. In this case, the installation of control marks is carried out on both sides of the grillage. A total of 25 control marks are to be installed: 12 marks on the northern foundation and 13 control marks on the southern foundation.
To protect against corrosion, the control deformation marks shall be painted, numbered with indelible paint, and tied to the corners of walls or ledges according to the scheme. The nearest points of the geodetic network shall be used to determine the planned elevation of the control marks.
The layout of control marks on the structures of the Arch hinged support gallery is shown in figure 1.
The planned geodetic network of the Shelter was constructed to ensure geodetic control over horizontal and vertical deformations.
The network includes a basic GPS network consisting of 9 points and a linear-angle network (triangulation) consisting of 16 points. The GPS network points are the starting points for determining the coordinates of the triangulation points.
Vertical movements of control marks of the lower tier are determined mainly by geometric leveling of class II, with a stroke misalignment of no more than

$$0{,}5\sqrt{n}\ мм, \tag{1}$$

with n – number of tripods in the course,
and where class I leveling lines are close to the structures, simultaneously with the main course. The length of the leveling stroke should not exceed 0.5 km. The value of the vertical movement of the control mark is determined by the difference between the marks obtained in the working and initial cycles. The tolerance for the accuracy of determining the settlements of the marks of the Shelter upper tiers, which can be determined only by remote method, for example, trigonometric leveling, should be taken as for the measurement accuracy class II, not more than 2 mm, especially for control marks located on the roof

and most exposed to temperature changes. For control marks placed on the upper levels of the Shelter, spatial (horizontal and vertical) displacements are determined by the following formulas (2):

$$\Delta X = X'' - X''; \qquad \Delta Y = Y'' - Y'; \quad \Delta H = H'' - H';$$

$$\ell = \sqrt{\Delta X^2 + \Delta Y^2} = \frac{\Delta X}{\cos \alpha_\ell} = \frac{\Delta Y}{\sin \alpha_\ell}; \qquad \alpha_\ell = \text{arc tg}\frac{\Delta Y}{\Delta X}; \qquad R = \sqrt{\ell^2 + \Delta H^2}, \tag{2}$$

with X’, Y’, H’ та X’’, Y’’, H’’ – equalized spatial coordinates of reference marks obtained from the initial and current measurement cycles; ΔX, ΔY, ΔH – are movements of the mark along spatial coordinate axes; *l*, *R* – horizontal and spatial vector of the mark movement; α_ℓ – the directional angle (azimuth) of the stamp movement direction (in the X, Y plane).

By uniting control marks into groups, for example, by belonging to separate tiers, structures, etc., and analyzing their movement, it is possible to derive a generalized vector of movement of the group of marks and its directional angle, in particular:

$$\overline{\Delta X} = \frac{1}{n}\sum_{i=1}^{n}\Delta X; \quad \overline{\Delta Y} = \frac{1}{n}\sum_{i=1}^{n}\Delta Y; \quad \overline{\Delta H} = \frac{1}{n}\sum_{i=1}^{n}\Delta H; \quad \bar{\ell} = \sqrt{\overline{\Delta X}^2 + \overline{\Delta Y}^2}; \quad \bar{\alpha}_\ell = \text{arc tg}\frac{\overline{\Delta Y}}{\overline{\Delta X}}, \tag{3}$$

with n – number of control marks in the group.

The degree of confidence in the generalized coordinate strain vector is characterized by its errors by the following formulas:

$$m_{\overline{\Delta X}} = m_X\sqrt{\frac{2}{n}}; \quad m_{\overline{\Delta Y}} = m_Y\sqrt{\frac{2}{n}}, \tag{4}$$

with m_X, m_Y - errors in determining the coordinate (abscissa or ordinate) of the mark.

By comparing these generalized deformation characteristics with each other, their changes depending on the height or location on the structure or building, it is possible to derive generalized characteristics to take into account the influence of other factors. One of these factors may be the temperature deformation factor, which has the greatest impact on the change in elevations and, in large structures, affects the amount of roll.

Discussions and results

The planned geodetic network was developed in stages as the scope of engineering and geodetic surveys at the site expanded and the required accuracy of deformation measurements was ensured (Винограденко, 2023; Vynohradenko, Siedov et. al., 2022).

An engineering and geodetic network was constructed with observation points located on the southern, western and northern sides of the Shelter. A number of control references and marks were fixed on the walls of the structure and its roof, which were selected taking into account potentially possible areas of settlement and deformation displacements of structures. The height position of the control marks located on the lower level of the Shelter was controlled by leveling of the I and II classes with reference to the depth references laid by the Ukrhydroproject Institute during the construction of the ChNPP. Control of the spatial position of control marks located on the upper tiers of the walls and roof of the facility was carried out by the method of direct angular notches from the points of the engineering and geodetic network.

The emergence of new tasks and changes in the construction situation at the Shelter necessitated the reconstruction of the planned and height geodetic network. The first reconstruction of the primary geodetic network was carried out by Ukrinzhgeodesiya in 1996, when a number of new points and references were laid, and modern engineering and geodetic equipment was used: a satellite geodetic system (GPS signal receivers 4600 by Trimble), an electronic total station TC 1800 and an electronic digital level NA 3003 by Leica (*Програма*, 2000). To measure the deformation displacements of the frame columns, a laser rangefinder "DISTO" by Leica was used.

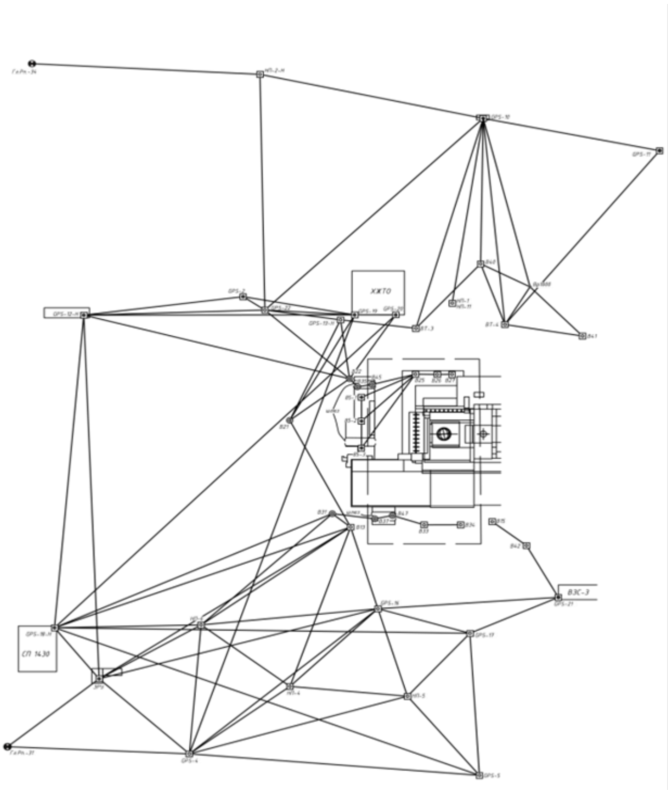
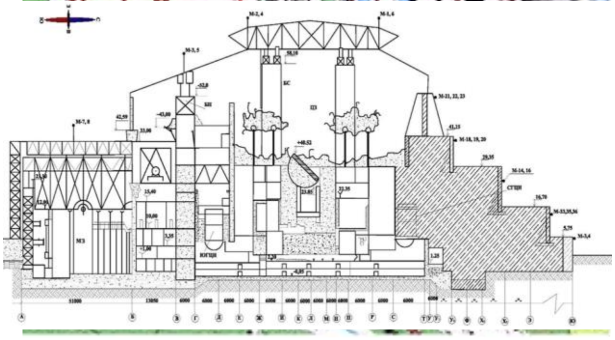


Figure 1. Scheme of the main planned geodetic reference network of the new safe confinement of the Shelter (source: developed by the author)

The second reconstruction of the planned geodetic network was performed due to the need to organise observations at new control marks M 9, M 10, M 11, M 12 and M 501, M 502, M 503, M 504, which resulted in the construction of a number of GPS network operating points in the Western Zone of the Shelter. In connection with the implementation of the Shelter transformation into an environmentally safe system, the planned geodetic network (and partially the height network) underwent a third reconstruction, which required a change in the structure of the network itself and placement of a part of the GPS network points on the roofs of the structures closest to the facility. The fourth reconstruction of the geodetic network was carried out in connection with the preparation of the site for the implementation of the action plan and partially for the construction of a new safe confinement (*Стратегія*, 2001). The fifth (last) reconstruction of the Shelter geodetic network was carried out in 2010. The results of observations performed at the facility show that vertical displacements of control references and marks reach 40 mm and increase annually. A map of the ChNPP industrial site is shown in figure 2 a, general view of the Shelter is shown in figure 2 b, and the layout of the main structures of the Shelter (section along axis 47) in figure 2 c.

It is an obvious fact that buildings in operation undergo gradual changes in the structure and properties of materials, and they are gradually destroyed by external factors: mechanical, physical, biological, chemical, etc. (erosion, corrosion). In the case of erosion, the greatest danger is posed by groundwater impact on the foundation under the building. Depending on the effects of air, water, and soil, different types of corrosion occur. The destruction of the outer parts of brick walls (weathering) occurs under the influence of temperature changes, alternating winds, moisture and drying, and freezing of water in the pores. On the surface, corrosion is caused by the penetration of water vapor into the pores and hygroscopic cracks of building structures. Another cause of corrosion damage to building structures is oxidation (*Розробка*, 2015).

B



A

C

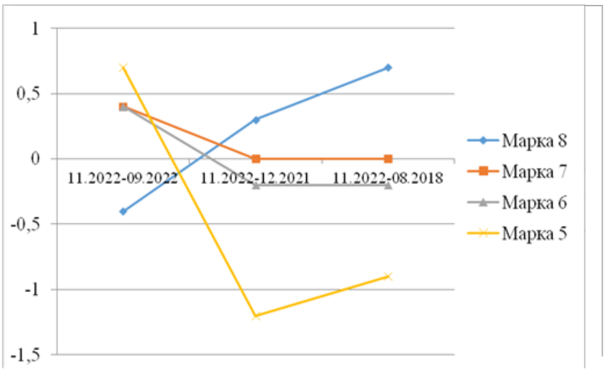
Figure 2, a - Map of the location of the Chornobyl NPP industrial site facilities; **b -** General view of the Shelter; **c -** Scheme of Shelter main structures location (section along axis 47) (source: developed by the author)

In addition to the significant material costs associated with restoring the operational properties of structures, their consequences lead to social and environmental damage. Therefore, it is important to correctly and timely assess the condition of structures, predict the possible development of defects and develop measures to stabilize or eliminate them. To do this, it is necessary to have an understanding of the mechanism of destruction and amortization of structural elements during operation and the impact of environmental factors on building structures.

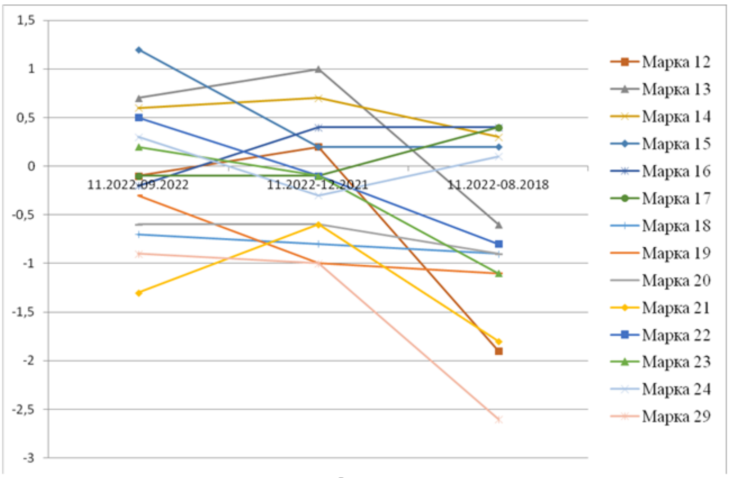
Observations during the monitoring process consist of controlling vertical and horizontal displacements of characteristic points and lines:

1. To observe vertical deviations (precipitation monitoring), so-called sedimentary marks are placed in the foundation, and these marks are periodically leveled. The difference in the height of the marks after comparing the data from different measurement cycles characterizes the size of the deformations and their rate. If uneven settlement leads to the development of crack deformations, they also become objects of monitoring. When laying sedimentary marks, the conditions of access to them and the possibility of installing a leveling rail on them should be taken into account, as a rule, at 0.4-0.8 meters from the level of the blind area or the level of the clean floor. Sedimentary deformation marks should be painted with indelible demasking paint, numbered and tied to the corners of walls or ledges.
2. The second aspect of geodetic monitoring is the control of horizontal displacement of vertical structures: columns, walls, etc. The degree of influence of the factors in each case may vary in intensity, but in each case, the main factor in extending the life of the building is the timely detection of major damages and defects in the building, which is followed by their elimination.

The results of geodetic observations of vertical and horizontal displacements of deformation marks, the dynamics of changes in the vertical displacements of control marks between the research cycles installed on the building of the fire water supply pumping station (FWS), the building of electrical devices (BED) and the technological building (TB) are shown in figures 3 a, b, c.



A **B**



C

Figure 3. Dynamics of vertical movements of control marks between observation cycles: **a -** installed on the FWS building; **b -** installed on the BED building; **c -** installed on the TB building (source: developed by the author)

Figure 3 describes the vertical and horizontal spatial displacements of the control and deformation marks installed on the building structures, as well as the total (sum) linear deviations and roll.

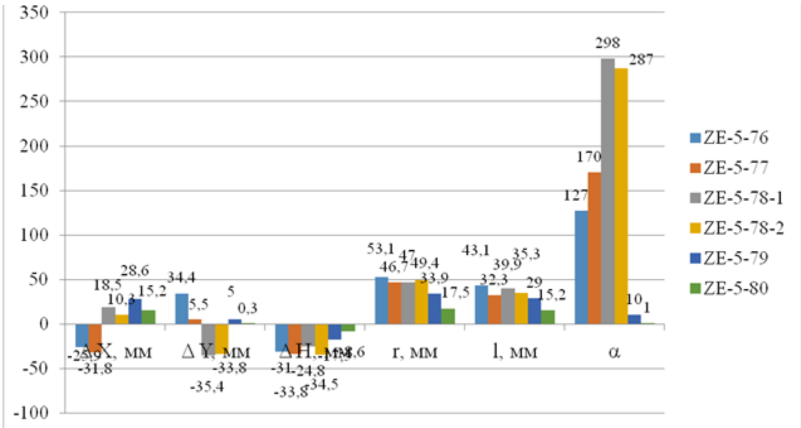


Figure 4. Dynamics of spatial displacements of control marks of NSC arch structures in the period 08.2018 - 11.2022 (source: developed by the author)

Based on the results of settlements and deformations observations, a technical report is prepared. If necessary, a forecast is made and recommendations are provided on measures to prevent the adverse effects of excessive deformations.

Conclusions and proposals

The analysis of the geodetic network, prerequisites and factors of the need for geodetic monitoring of settlements and deformations of the ChNPP Shelter structures, in particular, the values of horizontal and vertical displacements of control marks, in observation cycles, shows that the process of deformation of the NSC complex and adjacent buildings and structures continues. To analyze the displacements of control marks for a year, which is an integral part of monitoring the condition of NSC building structures, operational limits of safe operation were established, based on the fact that geodetic measurements are compared between the same observation seasons for a year with insignificant fluctuations in measurement temperatures. The obtained results will be used as initial data to track the dynamics of displacements, stability of building structures and take timely measures to prevent structural failure and predict emergencies of the NSC complex, as well as auxiliary buildings and structures.

The dynamics of control marks displacement between the cycles of two years of observations does not significantly manifest itself and does not exceed the permissible displacement parameters specified in the regulatory document "Technological Regulations for the Operation of the NSC-OU Complex", which may indicate a satisfactory condition of the complex building structures in general.

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