Study of static and dynamic geometric characteristics of buildings

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Abstract. It is impossible to get a truthful overview of the strain-stress state of any object using the methods recommended by the current regulatory documents for determining deformations. This paper implements the proposed method of determining the spatial geometry of an object. Such a method allows obtaining a detailed picture of deformations, on the basis of which it is possible to develop a qualitative project to restore its operational reliability. The rolls were determined according to 38 vertical sections (9 measurement cycles in total) for a building with a classic facade and 53 vertical sections (2 measurement cycles in total). Besides, five cycles of determination the settlement of structure were performed. The trigonometric leveling was used to control the horizontal position of different level building structures (top of window aperture of the 2nd floor). Elevations of horizontal building structures were determined in different conditional systems of heights. Elevations of horizontal building structures were determined in a single conditional system of heights. The results of the method are presented in graphical and tabular form.

1. Introduction

The methods of studying building deformations recommended by the current regulatory instruments require further improvement. Thus, it is recommended to use generalized roll values, settlements of the building foundation, and in some cases deflections, to determine deformations of buildings and structures in regulatory documents, which cannot sufficiently reflect the real picture of deformed state of buildings and structures [1–6]. Based on such results, it is impossible to determine a real picture of the stress-strain state and to make a viable project to restore its design geometry.

The proposed method – the method of determining the spatial geometry of an object – defines a larger number of geometric parameters – settlement, horizontality of horizontally oriented structures, a set of rolls on separate vertical sections, characterizing in full and in detail the deformed state of the building. This method makes it possible to detect stress zones caused by deformations of engineering structures, which is necessary to restore the spatial geometry of the building without additional deformations and faults [6–11].
2. Methods and materials
Static and dynamic deformation characteristics were studied on the example of the shopping center building with built-in fitness club located at 133/177 Krasnoarmeyskaya Str., Moscow.

The work was carried out using the latest geodetic measurement tools, such as:
- total station instrument GTS-102N;
- high-accuracy electronic geodetic level TrimbleDINI 0.3;
- invar levelling staff LD11 NedoTrimble;
- invar levelling staff LD12 NedoTrimble;
- metal measuring reel Geobox PK2–50 No. 7;
- sliding calipers (0–300) mm No. GK11275363;
- metal measuring reel 1000 mm No. 21051;
- ultrasonic tester UK 1401M No. 4011698;
- pachometer IPA-MG4 No. 2317.

These tools have verification or calibration certificates.

The office study of geodetic measurements was performed in the Credo_Dat program. Analysis and design of geometric parameters of objects is performed in ZWCAD software.

The purpose of preliminary inspection was to establish compliance of the layout and structural diagrams of existing structures with the requirements of technical documentation. During the inspection, the most damaged sections of the structures were revealed, as well as bearing elements under the most unfavorable conditions of operation. The general condition of the structures was visually assessed: presence of wetted concrete sections, condition of protective coating, presence of corrosion, etc. Thus, the preliminary inspection made it possible to collect the information, which allowed clarifying the program and scope of instrumental works.

No defects of both the entire building and its individual elements were detected from the visual inspection.

Observations of settlement points are made in the system of heights close to Baltic from wall benchmarks.

Observations of settlement points are made in a conditional system of heights. The levelling line is laid in forward and reverse directions. The determination of settlement points in each cycle is made with the accuracy characterizing the mean quadratic error of determination of settlement points in a weak place not more than 1 mm (the most remote mark from original benchmarks), which is provided by the method of high-accuracy geometric leveling of the II class in accordance with the current regulatory documents. The settlement points are determined in the Baltic system of heights through geometrical levelling in forward and reverse directions. The average length of the directional ray was 25–30 m for the main traverse and 2–25 m for levelling of settlement points. This made it possible to reduce the time of observations at the station, to improve the reliability, quality and speed of monitoring the measurement process.

The height of the directional ray above the underlying surface of the earth was allowed not less than 0.5 m, shoulder inequality at the station – not more than 1 m, and accumulation of shoulder inequality in the section – not more than 2 m. According to Paragraph 3, GOST 24846–2012 (Soils. Measurement methods of base deformation settlements of buildings and structures) the geometric leveling is used as the main method to measure vertical displacements (settlement). Basic technical characteristics and tolerances for geometric leveling were adopted in accordance with regulatory requirements.

The defects of the closed levelling loop did not exceed the permissible value determined by the formula:

\[ f_{don} = \pm 5 \cdot M \cdot \sqrt{L} \text{ km}, \]  

where \( L \) – levelling line length in km.

Permissible misalignment of levelling line between settlement points did not exceed the following value.
\[ F_{h(адд)} \leq \pm 0.3 \text{ mm} \sqrt{n}, \] (2)

where \( n \) – number of levelling stations.

As a result of the levelling, cycle and accumulated vertical movements of settlement points were determined.

In geometrical sense, settlement is expressed by vertical sections lowered from initial to subsequent position of the settlement point. In cases where these lines for different brands are the same, the settlements are called even and when the lines are not equal, they are called uneven. The principle of processing repeated measurements is that there are differences in elevation of settlement points between measurement cycles. At the same time the following is defined:

- total settlement \( S_{i,полн,} \), the value of which is equal to the difference of elevations of the same point of the current \( H_{i,1(текущий)} \) and initial cycle of observations \( H_{i,1(первый)} \);

\[ S_{i,полн,} = H_{i,1(текущий)} - H_{i,1(первый)} \] (3)

- settlement between adjacent cycles \( S_{i,c,c.} \), the value of which is determined as the difference of elevations of the same point of the current \( H_{i-1,1(предыдущий)} \) and the previous \( H_{i,1(последний)} \) of the observation cycle; \( H_{i,1(последний)} \) цикла наблюдений;

\[ S_{i,c,c.} = H_{i,1(последний)} - H_{i-1,1(предыдущий)} \] (4)

- uniform settlement \( S_{(рав),} \), the value of which is equal to the minimum total settlement \( S_{min,назу,} \) of the total settlement points;

\[ S_{(рав),} = S_{min,назу,} \] (5)

- uneven settlement \( S_{(нерав),} \), the value of which is defined as the difference of the total settlement \( S_{i,назу,} \) and the uniform settlement \( S_{(рав),} \);

\[ S_{(нерав),} = S_{i,назу,} - S_{(рав),} \] (6)

The average settlement is calculated by the following formula:

\[ S_{ср,} = \frac{\sum S_{i}}{n} \] (7)

On the basis of calculated values of total settlement points the average monthly settlement rates \( \nu_i \) are defined as follows:

\[ \nu_i = \frac{\Delta S_i}{t}, \] (8)

where \( \Delta S = S_{i+1} - S_i \) – inter-cycle settlement;

\( t \) – inter-cycle time period (usually expressed in months).

In the physical sense the velocities characterize the settlement dynamics.

Acceleration (attenuation) of settlement is calculated by the following formula:

\[ a_i = \frac{\nu_i - \nu_{i-1}}{t} \] (9)

This parameter characterizes the change in the dynamics of settlement (attenuation, acceleration).

Roll measurement was performed according to the following procedure. The device on the tripod was installed at a distance approximately equal to the height of the building under control. The coordinate system of the electronic total station was oriented parallel to the controlled plane (building wall). Then, in a single coordinate system, the device coordinated the points under study located in characteristic places of the building. The measurement results were automatically recorded by an electronic total station in the selected tool file. This file was translated to a computer after the measurements were made. After that, it was imported into the Credo_Dat program intended for camera
processing of field engineering and geodetic measurements. In this program, the polar coordinate system of the electronic total station was converted into a rectangular Cartesian coordinate system. Then the resulting 3D point coordinates were exported to the *.dxf (AutoCAD) format. The resulting file was then opened in AutoCAD, where drawing, measurement and analysis of the basic geometry of the building was performed.

The rolls of the structure can be expressed in relative and absolute measures. Besides, there are private $q_x$, $q_y$ (for some coordinate plane) and absolute $Q$ (full roll) for both individual elements and the structure as a whole.

In determining the rolls of the studied building, the method of coordination was used. This method defines the rectangular coordinates of the top $(x_v, y_v, z_v)$ and bottom point $(x_n, y_n, z_m)$ of the construction structure in various ways. It is more rational to implement this method using a modern electronic total station).

The electronic total station measures a horizontal angle $\alpha$, a vertical angle $\nu$ and an inclined distance $s$. The following working formulas are used to convert the polar coordinate system to a rectangular Cartesian coordinate system:

$$h = s \cdot \sin \nu; \quad x = s \cdot \cos \nu \cdot \cos \alpha$$

$$y = s \cdot \cos \nu \cdot \sin \alpha.$$  \hspace{1cm} (10)

Private rolls were determined by the following formulas:

$$q_x = x_1 - x_2; \quad q_y = y_1 - y_2.$$  \hspace{1cm} (12)

The absolute (total) roll $Q$ is calculated by the following formula:

$$Q = \sqrt{q_x^2 + q_y^2}.$$  \hspace{1cm} (13)

where $q_x$ and $q_y$ – private rolls along $X$ and $Y$, respectively

Absolute roll orientation angle $\theta$ is calculated by the following formula:

$$\theta = \arctg \left( \frac{q_x}{q_y} \right).$$  \hspace{1cm} (14)

The geometry of the building was controlled from 6 stations.

The trigonometric leveling was used to control the horizontal position of different level building structures (top of window aperture of the 2nd floor). Elevations of horizontal building structures were determined in different conditional systems of heights. Elevations of horizontal building structures were determined in a single conditional system of heights. The point of the horizontal construction structure having the highest conditional point was taken as “0”, hence, all other points have a negative sign.

![Figure 1. Diagram of roll determination via coordination method](image-url)
3. Results

Figure 2 (Curves of settlement points) shows the settlement curves. This figure shows that the average settlement of the whole building, for the current observation period (from May to December) made 1.0 mm, and for the whole year (2016) it made 1.1 mm. The average accumulated settlement of the entire building was 4.2 mm. The largest accumulated settlement (since the beginning of observations) is recorded for point No. 9 (4.5 mm), No. 10 (4.5 mm), No. 23 (5.2 mm) and No. 24 (2.7 mm). The largest settlement in 2016 was recorded at points No. 15, 16, 17 and amounted to about 2 mm.

Figure 2. Settlement point curves

Figure 3 (Building roll diagram as of 16.12.2015) and Figure 4 (Building roll diagram as of 07.11.2016) graphically presents the results of the building rolls as of 16.12.2015 and 07.11.2016. These figures show the total and private rolls of all controlled building structures (wall edges and planes) in mm, as well as the complete roll of the whole building.

Figure 3. Building roll diagram as of 16.12.2015
This figure shows that the complete roll of the whole building makes 37 mm and is placed in the south-east direction.

In accordance with Section 5, GOST 24846-2012 (Soils. Measurement methods of base deformations of buildings and structures), the limiting errors of roll measurement depending on height $H$ should not exceed $0.0001 \cdot H$ for civil buildings and structures. In our case (at $H \approx 25$ m) the limiting error of roll measurement makes 2.5 mm. This measurement accuracy is ensured by the device used (electronic total station).

**Figure 4.** Building roll diagram as of 07.11.2016

**Figure 5.** Results of horizontal position control of building structures

According to SNiP 2.02.01-83 (Foundations of buildings and structures), the permissible value is the roll value, which does not exceed $0.005 \cdot H$. Therefore with a height of the building of $H \approx 25$ m, the admissible roll of the building is equal to $125$ mm. All rolls of building structures do not exceed this tolerance.
The results of horizontality control of building structures are schematically shown in Fig. 5. The results of conditional elevations are given in meters. This figure shows that along the north facade of the building, the top of the window aperture of the 2nd floor bent by about 20 mm. For all other elevations, the elevations of the 2nd floor window aperture change within the measurement errors.

4. Conclusion
The study made it possible to conclude the following:
1. The visual inspection of the whole building and its individual elements did not reveal any deformation defects.
2. The recorded results of settlement points are practically within the limits of instrumental errors of observations. The maximum accumulated settlement is recorded in points No. 6 and No. 9 (0.6 mm). The minimum settlement is recorded in point No. 12 (0.3 mm). All settlement points do not exceed the permissible limit.
3. Full roll of the entire building equals 37 mm and is placed in the southeast direction. All fixed rolls of building structures do not exceed the permissible limit of 125 mm established by regulatory documents.
4. According to the results of the horizontal control of the building structures, it was determined that on the northern facade of the building, the top of the window aperture of the 2nd floor bent by about 20 mm. For all other elevations, the elevations of the 2nd floor window aperture change within the measurement errors.
5. The building is in the permissible design operating mode.
6. More complete analysis of the geometric characteristics of the building structures will be carried out based on the results of the next measurement cycle.

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