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Orginal Article

Geodetic monitoring of the subsidence of a multi-storey building foundation

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Abstract: The presented study is devoted to determining the stability of the foundation of a seven-storey building located in Ivano-Frankivsk (Ukraine). A programme of surveying works was developed, taking into account its condition and configuration features. The project algorithm included laying deformation marks in the building foundation, performing geodetic observations using the method of high-precision geometric levelling, and processing and interpreting the results. The article provides an analysis of changes in the elevations of the building's deformation marks based on data from five series of observations carried out between 09/2019 and 06/2024. The results obtained indicate uneven subsidence of the foundation around the perimeter of the building, which led to the appearance of cracks.

Keywords: deformation of the building, geometric levelling with a short beam, deformation observation programme, deformation mark, subsidence

1. Introduction

Prompt observation of deformations in structures is indeed crucial for determining their strength and stability in order to prevent collapse or to provide timely information about an emergency condition. Observations are conducted from the start of construction through high-precision, thorough and systematic geodetic measurements, which vary in nature. Geodetic measurements must be supported by a highly-accurate and stable horizontal and vertical survey network.

The measurement of deformation values discontinued (or reduced to the required scope) only once the settlement processes have stabilised. Therefore, a characteristic feature of surveying works is their systematic repetition over a fairly long period of time, depending on the stability of the underlying soils. These observations include the measurement of settlement bases and foundations, determining the horizontal displacement of structures, and monitoring the tilting of high-rise buildings, pipes, towers, etc. At this stage, geodetic works are performed using high-precision instruments according to a specially developed programme.

2. Analysis of recent studies and publications regarding the solution to this problem

The geodetic monitoring of deformations of high-rise buildings and structures is considered in [1,2]. The analysis is aimed at processing and comparing the results of several cycles of observations, as well as ensuring the monitoring of the deformed state of an object over its entire surface. Such data from geodetic monitoring of displacements and deformations form the basis for generating an approximating linear-harmonic function. Mamajonova et al. [3] present the rules for using the visual control method, the purpose of which is to detect minor visible signs of deformations at an early stage or changes in the position of structural elements of an object. The aim of this study is to create appropriate conditions for the safe operation of structures by the early detection of any negative changes in the state of tensile deformation and the immediate implementation of measures to localise them. The methods indicated are based on typical ground geodetic measurements.

Shults et al. [4] describe an approach to solving the problem by means of an integrated GNSS-system and non-metric cameras with QR-coded targets. This system is positioned as an inexpensive surveillance method developed on the basis of computer vision technology with GNSS support. The proposed method enables the identification of changes in the geometric parameters of a structure under the impact of external factors or loads, which serves as a foundation for anticipating future deformation values.

Particular attention is paid to remote methods of subsidence monitoring in Pakshyn et al. [5]. The feasibility of using the radar interferometry method to monitor the vertical deformations of infrastructure objects is substantiated using the example of the educational building of the Ivano-Frankivsk National Technical University of Oil and Gas. Based on the radar information received, the data set was processed using the Persistent Scatterers Interferometry method. As a result, the average values of the vertical displacement rate of the university territory were determined and confirmed by the results of GNSS-observations.

Laser scanning methods are of great scientific interest [6,7]. Their advantage lies un the rapid acquisition of a large amount of information; however, a significant amount of time is required to process the data received. Zhou et al. [8] suggest using automatic non-contact monitoring systems, and developing algorithms and programmes to address these challenges.

Kaartinen et al. [9] describe projects developed for monitoring the condition of structures using LiDAR, aimed at detecting cracks, deformations, defects, or changes in structures occurring over time. The research covers a wide range of civil infrastructure systems, including bridges, roads and pavements, tunnels and arches, and post-disaster assessments. The vast potential of mobile and stationary LiDAR devices for damage detection is highlighted, as scanning provides detailed geometric information on the assessed structures.

The research into laser scanning for enclosed structures is also of great interest [10]. It describes the use of less expensive equipment and demonstrates a highly effective method of point-cloud processing to achieve self-adaptive measurements based on the characteristics of enclosed structures. The focus in Maru et al. [11] is on the relative positioning of separate elements of a building, which is particularly significant for detecting and predicting deformation processes.

However, none of the above methods provides the same accuracy in recording subsidence values as high-precision geometric levelling with a short beam. Thus, in paragraph 6.2 of the Guidelines [12], it is recommended that deformations of buildings and structures be monitored using exactly this method, with the measurement methodology developed individually for each object and taking into account “the foundation structure, loads on separate parts of the basement, geological and hydrogeological conditions.” Therefore, it was decided to monitor the subsidence at the object under study using the method of high-precision geometric levelling with a short beam.

3. Presentation of the main material

Monitoring of the structural condition includes many methods and technologies that allow for the control of a wide range of building parameters [13,14]. When a factor that leads to a sudden change in the normal course of deformations is activated (such as a change in the load on the foundation, a change in the temperature of the environment or the building structure, tectonic forces, war, etc.), emergency observations are carried out.

Possible causes of deformations are studied for the engineering interpretation of the results of deformation measurements. The main focus is on geological, hydrogeological and climatic data, including the thickness of individual soil layers, groundwater levels, physical and mechanical properties of soils, and other relevant information [15]. In some cases, special observations of the thermal regime of soils and groundwater and meteorological conditions are organised, construction and technological loads are taken into account, and deformations are measured simultaneously.

3.1. Geodetic observations of subsidence of the multi-storey building foundation in Ivano-Frankivsk city

The object of the study is a seven-storey public building constructed in the mid-1980s. The area is characterised by the presence of near-surface water. For this reason, works were carried out during construction to dry the rocks beneath the foundation. A granulometric analysis of the soil showed that it consisted mainly of loam. This class of soil is prone to subsidence deformations. Due to the appearance of cracks in the building’s walls, a geodetic monitoring programme was developed in 2019, and a reconnaissance of the surrounding area was conducted [16]. A total of 63 deformation marks were installed in the foundation, as required by the building's complex configuration. The locations of these marks, selected in accordance with regulatory requirements, are shown in Fig. 1.

Between 09/2019 and 06/2024, five series of measurements were carried out at the site using the high-precision electronic digital level DL-501, with automatic readings taken by a barcode level rod. Before each series of observations, the level was calibrated according to the procedures specified in the device's operation manual. Observations were conducted using a method that ensures a mean squared error in determining the elevation of the weakest point in the network of no more than 1 mm.

In all series, the measurement scheme includes a system of closed level traverses connecting the deformation marks installed in the foundation of the studied building with initial benchmarks of the national levelling network located in the foundations of five- and nine-storey buildings: Rp 1364, Rp 1327, and Rp 1319, as well as two benchmarks in the foundation of a ventilation pipe near the research object (Fig. 2). Figure 2 shows the calculation results for actual levelling misclosures, which were used to verify the accuracy of the measurement results.

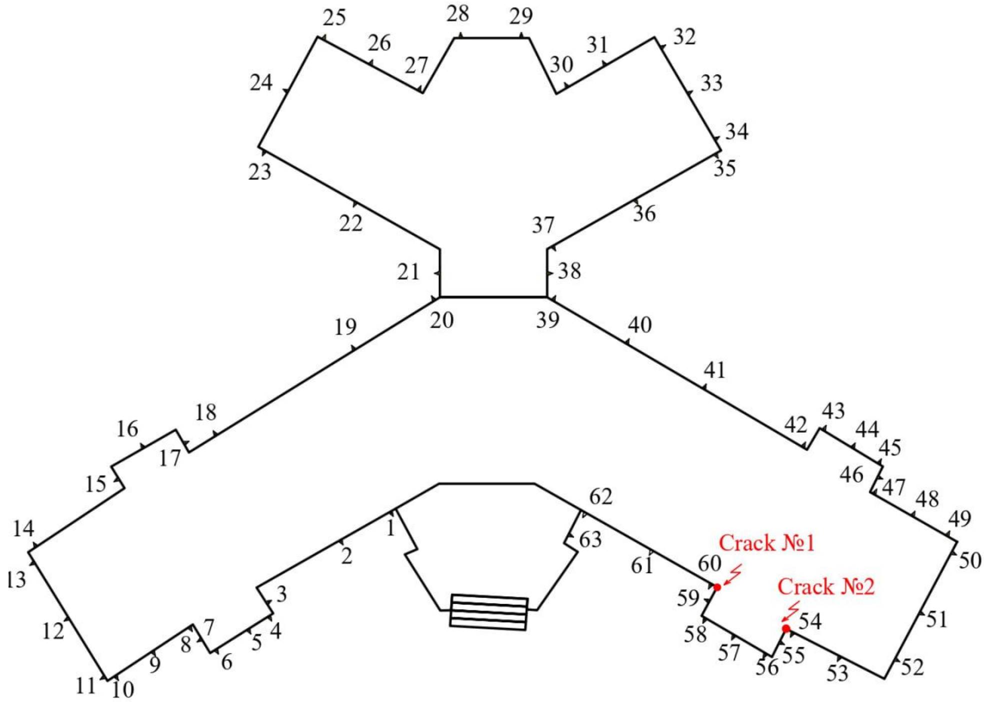

Fig. 1. Scheme of the deformation marks location. *Source:* the author's research

The mean squared error in determining the height difference at a levelling station was not permitted to exceed 0.2 mm. High precision was achieved using rank B geometric levelling [17] with a short beam, in compliance with the following requirements:

- the length of the levelling rod did not exceed 1.8 m;
- the allowable difference in sight length at the station did not exceed 1.0 m;
- at the connecting points of lines, the rod was placed only on a special base plate;
- at the stations, the instrument and levelling base plates were placed only on hard soil or concrete;
- -the following allowable deviations were applied during measurement control: the differences in height determined at two instrument setups were not allowed to exceed 0.6 mm for each stretch. Allowable misclosures were assumed depending on the number of stations (n), according to the formula:

$$f_h^{al} = 0.3\sqrt{n} \quad (1)$$

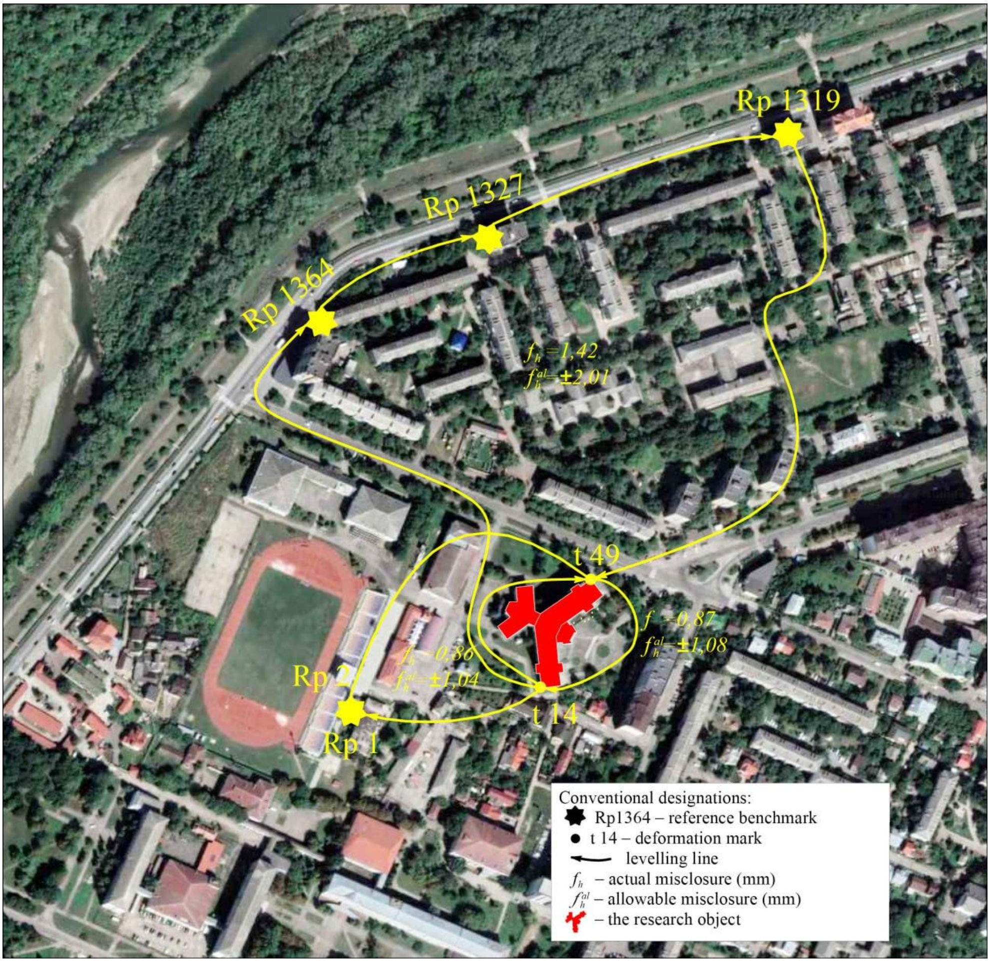

Fig. 2. Scheme of the projected levelling network. *Source:* the author's research

The initial reference benchmarks Rp 1364, Rp 1327, Rp 1319, Rp1 and Rp2 may be considered stable, as the buildings in whose foundations they are installed were constructed 50–70 years ago, and the settlement processes have already ceased. The data from each series of observations were adjusted using the parametric method, while the accuracy of measurements was assessed using a specially developed software package based on solving a nonlinear programming optimisation problem.

A fragment of the listing of the automated processing results, containing data on the aligned elevations of selected deformation marks and the subsidence values for the entire period, is presented in Table 1 below.

For the period from 09/2019 to 06/2024, the maximum value of subsidence was recorded at deformation mark No. 59, amounting to (-7.7 mm). It should be noted that the minimum, maximum, and average values of subsidence indicated in Table 1 were calculated based on the results of observations of all 63 marks (see Fig. 1). Table 1 provides sample information only for the marks with the largest subsidence values. In column 2020, there is no data for marks 43 and 47 due to the lack of access to them at that time.

Table 1. Elevations of the deformation marks of the multi-storey building foundation in Ivano-Frankivsk city. *Source:* the author's research

Deformation mark	Elevations of the deformation marks (mm)					Subsidence (mm)
	09.2019	08.2020	06.2022	05.2024	06.2024	During the entire period
12	247018.1	247016.9	247016.1	247014.9	247013.3	-4.8
43	246278.4		246276.3	246275.6	246275.9	-2.5
44	246293.3	246291.5	246290.9	246290.3	246290.3	-3.0
45	246495.4	246493.0	246492.6	246492.4	246492.2	-3.2
46	246401.8	246399.4	246399.3	246398.4	246399.0	-2.8
47	246612.0		246609.7	246608.5	246609.2	-2.8
55	246737.0	246735.0	246734.4	246732.8	246733.3	-3.7
56	246317.6	246315.6	246315.1	246313.2	246313.9	-3.7
57	246336.9	246334.7	246334.3	246332.4	246332.9	-4.0
58	246678.6	246675.9	246674.9	246672.4	246672.5	-6.1
59	246702.9	246698.7	246697.7	246695.3	246695.2	-7.7
					MAX	-0.5
					MIN	-7.7
					AVER	-1.9

The recorded values of subsidence in the areas of marks 43–47 and 55–59, ranging from (-2.5 mm) to (-7.7 mm), indicate that the foundations of the corresponding stairwells are gradually settling relative to the main foundation of the building, which is also illustrated in the graph below (Fig. 3). The graph shows the dynamics of deformation mark subsidence relative to the initial series of observations. Thus, the elevations of the deformation marks from the 09/2019 series are considered the initial values, with their subsidence equal to zero (brown line on the graph). In subsequent series of observations, the value of subsidence for each deformation mark was calculated as the difference between its elevation in the current series and that in the initial (09/2019) series. The subsidence curve for 06/2024 was constructed using the values from the last column of Table 1.

An additional confirmation of this is the formation of cracks No. 1 and No. 2 (Fig. 4) at the joints between the stairwell and the load-bearing wall in the area of deformation marks 55 and 59. In order to determine the causes of the subsidence, it is recommended that relevant specialists analyse the structural features of the foundations of both the stairwells and the main building, taking into account the geological characteristics of the soils and the groundwater beneath the foundation.

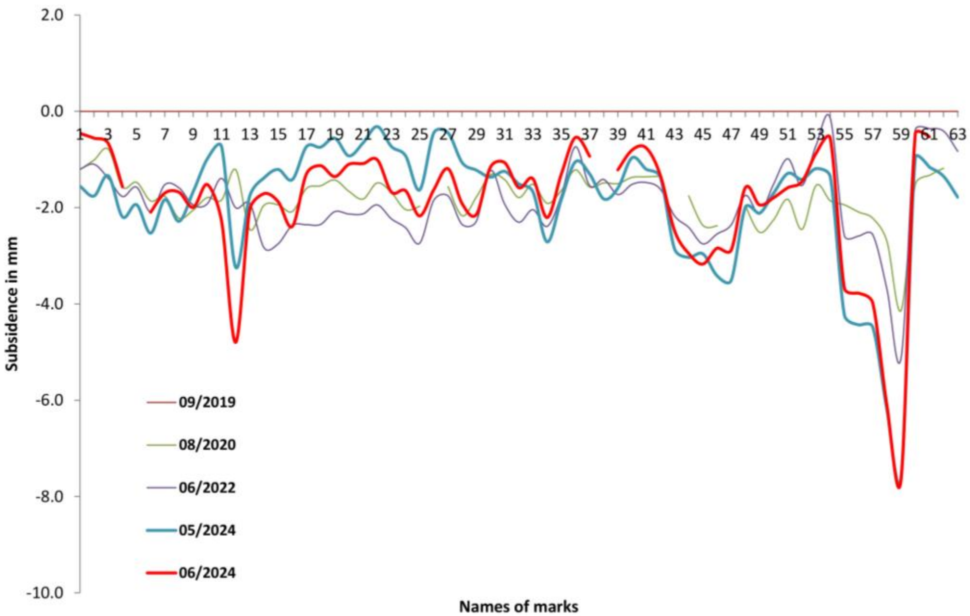

Fig. 3. The graph of subsidence of the foundation deformation marks based on the results of measurements from 09/2019 to 06/2024. *Source:* the author's research

Fig. 4. Photo documentation of cracks No. 1 and No. 2 on the building facade. *Source:* the author's research

At mark 12, a subsidence value of (-4.8 mm) was recorded, which coincides with the formation of a longitudinal crack in the foundation between marks 11 and 13.

To better visualise the settlement process of the building's foundation, a 3D model was created using the Surfer graphic editor (Fig. 5). Figure 5 clearly shows that the results of the subsidence monitoring revealed anomalies at marks 12, 43–47, and 55–59, which have led to cracks in the building's structural elements. Since such monitoring was not carried out prior to 2019, it is not possible to determine whether the foundation was deformed during the initial years following the building’s construction or during its long-term operation.

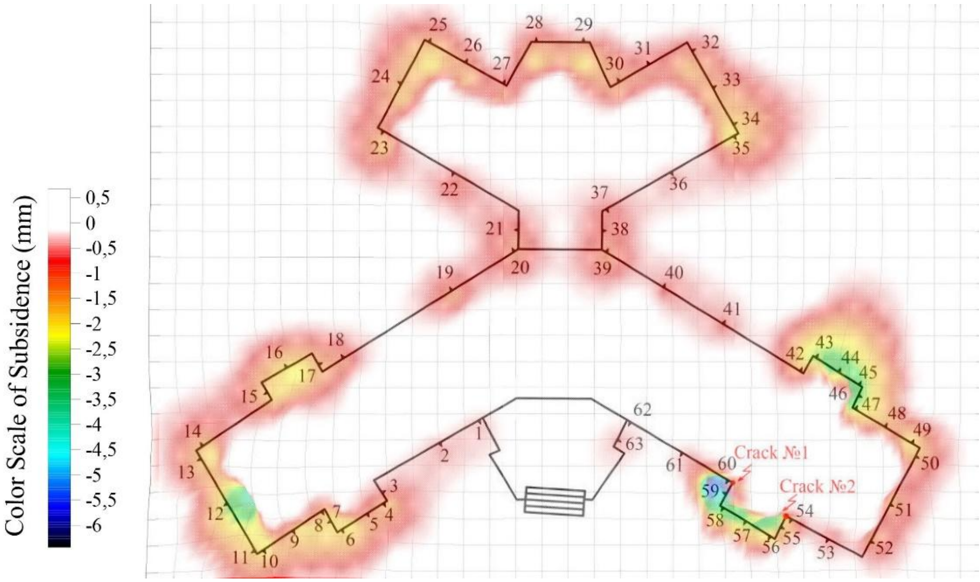

Fig. 5. 3D model of the foundation subsidence as of 06/2024

Uneven foundation subsidence often leads to cracks in building elements, significant tilting of structures, and, in some cases, the collapse of the entire construction [18]. The main cause of this is an increase in the moisture content of the foundation soil due to leakage from water supply networks, improper organisation of surface water drainage, etc. However, the timely detection of uneven subsidence dynamics allows for the implementation of measures to halt the process [19].

4. Conclusions and consequences of the research

Based on the analysis of previous studies on the optimal method for subsidence monitoring, it has been established that high-precision geometric levelling with a short beam is the most suitable for this purpose. Considering the structural features of the foundation and the entire building, 63 deformation marks were installed. Their elevations were determined in five series of observations relative to five initial benchmarks of the high-precision national levelling network.

The results of geodetic monitoring for the period from 09/2019 to 06/2024 confirm the presence of a subsidence process in the foundations of the stairwells on the right wing of the building relative to the main foundation (subsidence values ranging from -2.5 mm to -7.7 mm). During the period studied, the average subsidence of the foundation deformation marks was recorded as (-1.9 mm). However, the greatest threat to the building arises from the uneven subsidence of the deformation marks (ranging from -0.5 mm to -7.7 mm), which has led to the formation of cracks both in the walls (Fig. 4) and in the foundation.

It is advisable to expand the geodetic monitoring to include observations of the upper main body of the building. The following parameters can be determined: deviation from the vertical axis and other deformations of individual structural elements or the entire building, as well as the opening of cracks and the dynamics of their development. Tilt measurements can be carried out using the methods of inclined projection, angular or linear-angular intersections, stereophotogrammetry, and terrestrial laser scanning. In this case, it is recommended to periodically perform laser scanning of the building facades, and to observe the dynamics of vertical and horizontal deformations using the resulting 3D models. To monitor the rate of crack opening, electronic or mechanical resistance sensors should be installed at selected locations. It is crucial to take into account the geological and hydrogeological characteristics of the soils in the building area, as well as their potential impact on further deformation processes developing in the building structures.

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