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THE GEODETIC MONITORING OF DEFORMATIONS OF A HIGH-RISE BUILDING USING GROUND-BASED LASER SCANNING TECHNOLOGY

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The article justifies the use of laser-scanning systems for geodetic monitoring of high-rise buildings and structures. Contemporary methods allow solving comprehensively the main tasks of geodetic monitoring. During the monitoring of high-rise objects, not only the main geometric parameters of the objects should be taken into account. The main importance should be given to the mutual arrangement of individual building elements, which is especially important for identifying and predicting deformation processes. Laser scanning coordinate measuring systems are designed to measure the object coordinate points to determine the object's geometric dimensions. The principle of GLS operation is to measure the point coordinates in space by the polar method. Distance is measured by a laser rangefinder using a pulse method with signal digitization technology. The advantage of this approach is a smaller amount of time spent on the creation of a primary survey network. At that, the laying of scanner ray paths is most effective when carrying out ground-based laser scanning of linear structures. But it is advisable to apply its construction elements within the framework of the developed methodology. The development and implementation of new technologies for geodetic work performance, supported by an appropriate level of automation, is always carried out to reduce the time required for data collection and processing. The RiSCAN PRO program is a project-oriented product, i.e. the entire volume of data obtained as a part of a single measurement project is structured and stored according to the RiSCAN PRO project structure.

Keywords: monitoring, control point, deformation, stability, laser scanning

1 INTRODUCTION

In Kazakhstan, the Northern Tien Shan, at the foot of which is the southern metropolis of Almaty is the most seismic territory. The probability of strong earthquakes in Almaty is high. Currently, more than two million people live in the city. There is a high concentration of industrial civil enterprises, government, educational institutions, and major global business centers.

All this leads to a change in the requirements for the accuracy of determining the geometric dimensions of buildings and structures, as well as to determination errors that occur during the installation of structures, laying the foundation of buildings and structures [1].

At the same time, the probability of soil surface deformations for large megacities, such as Almaty, becomes quite significant. Deformations can be caused by both man-made and quite natural factors, such as the pressure of buildings and structures on the ground, large-scale multi-storey construction, intensive development of underground space (metro lines, various kinds of communications, etc.), increased traffic flows, changes in the groundwater level, etc.

The main building of the Kazakh National University (KazNU) is a tower-type structure. Its height is much larger than the horizontal dimensions (the diameter of the foundation, and the sides of the base). Measurements during the study of the building have shown the following data

- Height – 68.377 m,
- Width – 37.187 m,
- Length – 15.858 m.

Building structural scheme is a metal frame made of columns and crossbars, on which external reinforced concrete wall panels were mounted. This solution made it possible to speed up the construction process and provided large spans and areas free of structures inside the building (Fig. 1) [2].

Fig. 1. The main building of the Al-Farabi Kazakh National University

The 17-storey building of the rector's office of Al-Farabi KazNU (KazGU) was built in 1978 being one of the highest buildings in the city. Al-Farabi KazNU is located on a picturesque plot of about 100 hectares, framed by two highways from the north and south – Timiryazev and al-Farabi streets. Even a small stream flows through the territory connecting the Botanical Garden and the Esentai River.

Deformations may be associated with the beginning of soaking of soils after their thawing. Usually, in built-up areas, the groundwater level rises significantly. The rate of its rise can be significant and reach 0.3-1.5 m/year [3]. In spring, snow melts, and meltwater can flood not only the surface layers of the soil but also go deeper into the base of the building. And this, in turn, can cause various processes, such as subsidence of soils, subsidence, and compaction of decompressed soil layers, suffusion of small soil particles, karstic phenomenon, etc. If a sharp increase in the activity of cracks is recorded in the spring period, then one should try to identify places and sources of moistening of the foundation soils. Often the sources of problems are the flow of meltwater into the basements of buildings, a destroyed blind area, backfill soil that passes water well, lack of surface drainage of meltwater due to terrain, incorrect vertical layout, blockages in sewers, etc. Therefore, it is necessary to carry out a forecast of flooding of the site and changes in the physical and mechanical properties of the bottom soils, to identify the possibility of changes in the chemical composition of groundwater and monitor situations related to the adjacent Esentai and Kerenbulak rivers.

Solving the problems of geodetic monitoring of high-rise buildings, aimed at ensuring their normal and trouble-free functioning, is based on using appropriate methods and technologies. At the same time, there is a tendency for their improvement, reorientation from the use of traditional instrument bases (theodolites, levelers, etc.) to a qualitatively new level, primarily associated with the automation of geodetic works.

Therefore, important is completeness and continuity of the collected data, which can be ensured using remote sensing techniques, in particular, the ground-based laser scanning technology (GLS) [4].

The exploratory survey technique using a laser scanner has made significant progress and in recent years has been introduced in the field of architecture in areasб such as civil engineering, architecture, archaeology, and industry. The 3D scanning process steps, proposed to create a point cloud using a ground-based laser scanner and combining them with software, can be used to measure both internal and external details of an object. This method is used in many fields, being one of the photogrammetric techniques that are widely employed to obtain a sequence of images (objects) and to measure the reconstruction of a 3D model [5-7].

The purpose of the present study is to develop methods and techniques for the production of instrumental observations of high-rise structures for a qualitative assessment of the building condition employing modern geodetic instruments (ground laser scanning)

The currently existing traditional methods of instrumental observations do not satisfy production, since they are very labor-intensive and do not allow obtaining data on hidden deformations of a high-rise structure necessary for a successful solution to problems associated with building deformations. Therefore, the task of improving the instrumental observation methods based on the use of the latest high-frequency and high-performance automated geodetic instruments is quite relevant [5].

The main purpose of monitoring is to determine the deformation values to assess the stability of the structure and take timely preventive measures to ensure its normal operation.

Using scanned material, one can create any drawing, three-dimensional model, video and solve many other problems.

As a result, using the data obtained, the point cloud is processed in the RiSCAN PRO program [8].

Processing types:

1. Sizing;

2. Flat drawings;
3. Three-dimensional models.

The ultimate goal is to define an approach and method to measure and monitor building surfaces. The present study shows a 3D model of the Al-Farabi KazNU building. Employing this method we obtained profiles, aspects, and 3D models of structures. An architectural overview of the structure was obtained using 3D data generated in RiSCAN PRO software.

2 METHODS

2.1 Research design

Traditional observation methods by geometric and trigonometric leveling, observation by linear-angular networks, and geodetic serifs methods are quite time-consuming due to a large number of measurements and manual data processing.

With developing photogrammetric and laser scanning measurement methods, it becomes possible to reduce the complexity of field observations based on an automated system.

Using laser scanning during observations allows determining the position of the working reference points in space and building a picture of the vector displacement of the reference points in time.

Since the object under study is located in an area, unstable in terms of impacting geological, hydrogeological, and technogenic conditions, the object needs to be monitored using modern automated devices such as a ground-based laser scanner.

For laser scanner-based high-precision instrumental observations, a scheme has been developed for conducting observations along a profile line over the working reference points from reference and connecting points, which allow ensuring the required accuracy under various geological, hydrogeological, and technogenic conditions of buildings and structures.

A new solution for monitoring the deformations of engineering structures is to combine the data obtained using metric three-dimensional models developed using GKS technology.

The essence of the GLS is to measure a set of points belonging to the surface of the object under study, using a laser scanning system (laser scanner or lidar). Regardless of the type of device and the attached software, the resulting data of fieldwork and primary processing is a **three-dimensional point model** (scan, point cloud) of the object under study, representing a set of points with known coordinates X, Y, Z (Fig. 2) [5, 8-13].

The three-dimensional coordinates of each point of the object under survey are calculated using the following formulas:

$$\begin{gathered} X = D \cdot \cos\varphi \cdot \sin\theta \\ Y = D \cdot \sin\varphi \cdot \sin\theta \\ Z = D \cdot \cos\theta \end{gathered} \tag{1}$$

For each specific scanner model, formulas (1) have an individual form, which takes into account the mismatch of the radiation source and the receiver, the eccentricity of the vertical and horizontal axes of device rotation, and other quantities that make up the scanner calibration parameters [4, 6].

2.2 Preparatory works for the GLS in the field environment

In this paper, we propose a GLS technique that allows real-time monitoring of changes in the geometry of objects of complex configuration.

To maximize the coverage of the most active terrain-forming processes by the measurement device, and to minimize the surfaces that were not intended to scanning (black spots), a preliminary study of the terrain was carried out using Google Earth resources, satellite images, and topographic maps. Scan points (scan positions) are plotted on the prepared sketch-map (Fig. 3). At that, if the terrain conditions change or the map materials are not correct, the scan points are adjusted depending on the site conditions [8, 14, 15].

The GLS method consists of three main stages: the selection of monitoring sites and the scanning point; ground-based laser scanning of the selected sites using a VZ-4000 3D scanner with maximum coverage of the scanned object; and cameral processing of the obtained data using the RiSCAN PRO program [15].

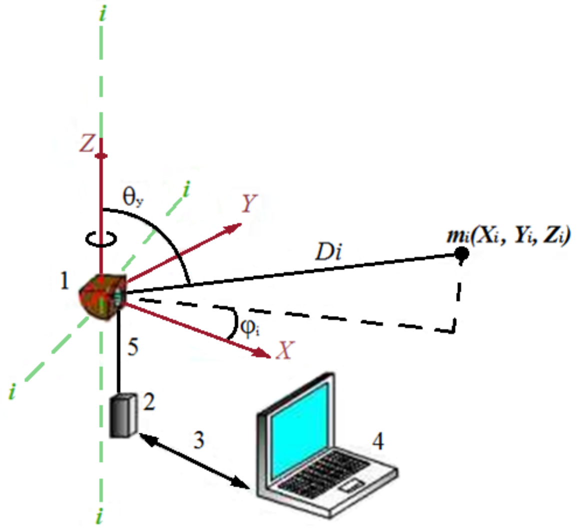


Fig. 2. Basic design elements of a ground-based laser scanner

Fig. 3. Sketch-map of the scanning point (scan position)

During the preparatory GLS work in the field environment, the following criteria for scanning the rector building of Al-Farabi KazNU were determined:

1) minimum distance to the object (5 m);
2) maximum distance to the object (4,000 m);
3) monitoring of diffusely scattering targets (walls, shrubs, and trees), to obtain a complete set of object surface data;
4) vertical scanning coverage range of 60°;
5) horizontal scan pitch of 0.03° (FrameRes);
6) measuring frequency of MeasProgram of 200 kHz (scanning range 1-2 km);
7) scans overlapping 10-15%;
8) determining the solid standing point of the scanner (scan positions). In our case, 11 observation points have been determined [16, 17].

2.3 Ground-based laser scanning of selected areas using the VZ-4000 3D scanner

Object scanning is usually performed using several scans obtained from different points of the scanner position in relation to the object being scanned. The scan is set to the mode of "Rectangular field of vision". Usually, the same angular increment is set for the structural and linear scan, so that the resulting point cloud has no distortion, but has a constant angular grid on both axes. The scanner head begins to rotate, collecting data in the rectangular scan mode. The rotation stops after the entire field of vision has been scanned [http://riegl.com/].

As a result of the cameral processing of the obtained field data using the RiSCAN PRO program the authors have received processed data consisting of the following components:

- registration of the scan position and multistation equalization (MSE);
- creating a single point cloud; purifying against "echo"; filtering against vegetation and non-natural constructed objects;
- comparative analysis of the point cloud for different periods;
- creating a digital terrain model.

2.4 Creating a single-point cloud

Upon completion of registration and equalization of all scanned positions, it is necessary to create a single-point cloud. A point cloud is a group of points with coordinates in a well-defined coordinate system. Due to the lack of a high-precision instrument for determining the coordinates, the authors used the coordinate system of the RiSCAN PRO software project. In addition to coordinates, each point from the point cloud allows defining important additional attributes, such as time mark, amplitude, reflectivity, and pulse shape deviation. When creating a single point cloud, the points were decimated i.e. the distance between the points (with X, Y, Z coordinates) was kept to 5, 10, and 20 centimeters to lighten the weight of the point cloud for further processing and obtaining final quantitative data.

The created single point cloud for each monitored area in individual projects of the RiSCAN PRO program (Fig. 4) is a convenient monolithic data material for further quantitative analysis [5, 9].

Fig. 4. Example of a point cloud of a building façade

RiSCAN PRO software is a project-oriented product, i.e. the entire data acquired in the framework of a single measurement campaign is organized and stored in the RiSCAN PRO project structure. This data include scans, the coordinates of the control points and tie points, as well as all the transformation matrices necessary to transform the data of multiple scans into a common well-defined coordinate system. Moreover, if the scanner is equipped with an additional high-resolution digital camera, the images taken by this camera are also processed by the RiSCAN PRO program. RiSCAN PRO is designed to reduce the time to acquire data in the field while offering tools for visual inspection of the overall completeness of data coverage in 3D right after acquisition in the field environment. Automated control point scans make it easy to place scan data in a pre-defined, high-resolution coordinate system. In addition to data collection, RiSCAN PRO has post-processing capabilities.

At this stage, it is important to formulate the goals and objectives of the laser scanning survey, to clarify the requirements for accuracy and the final product type. Based on this, the associated equipment is selected. The ground-based laser scanning of high-rise buildings and structures must be carried out using equipment that provides a sufficient measurement distance.

The scheme for calculating the maximum scanning distance *L* is shown in Fig. 4, where *H* is the object height, *h* is the lidar installation height, *S* is the horizontal distance from the lidar to the object, *a* is the maximum angle of incidence of the beam [12, 14, 18].

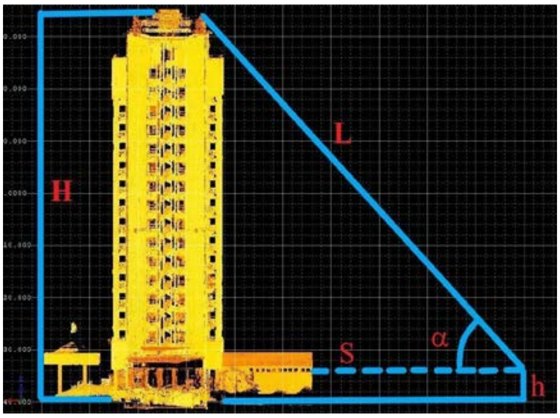


Fig. 5. Scheme for calculating the maximum scanning distance

Based on the diagram in Fig. 5, the maximum scanning distance is determined by the formula:

$$L = \sqrt{S^2 + (H - h)^2} \tag{2}$$

The angle of incidence of the beam is determined from the expression for X:

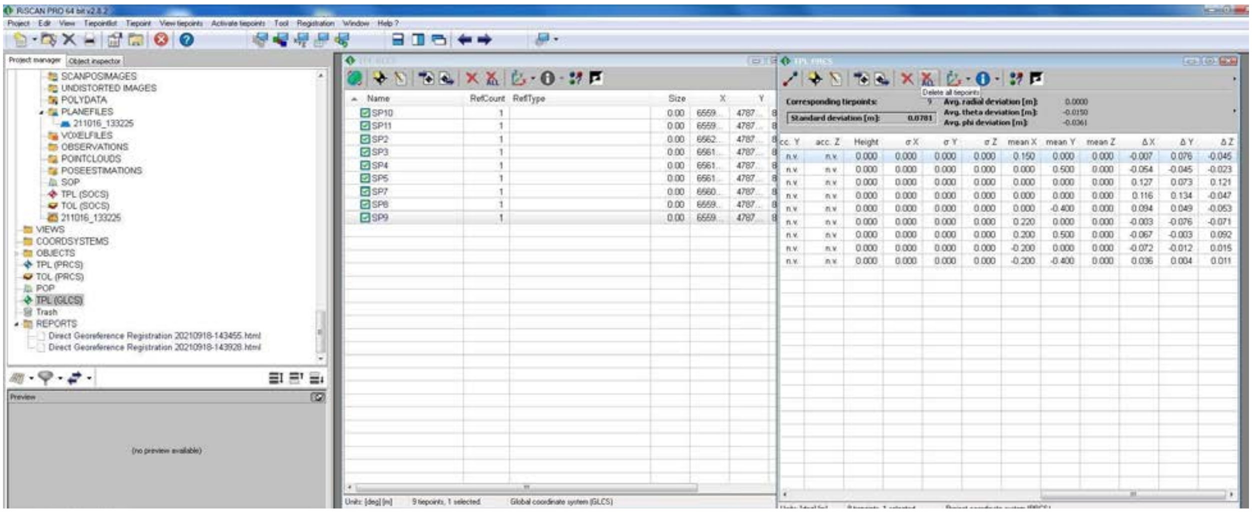
$$\alpha = arctg(\frac{H-h}{S}) \tag{3}$$

The software used to work with ground-based laser scanning data can be divided into two groups: control and processing. Processing software refers to programs that allow performing three-dimensional modeling based on laser scanning data. Modeling consists in the construction of solid models, polygonal and spline models of surfaces, and the creation of various drawings. The control software is designed to control the scanner, collect and store data, register scans, as well as to work with certain scanner models (scanner producing companies develop their in-house control software). The task of registering scans is one of the key problems for the control software, so developers pay a lot of attention to it. The article describes an approach to scan registration implemented in the RiSCAN PRO software product (Riegl Laser Measurement Systems GmbH, Austria). The RiSCAN PRO software implements the following methods for registering scans [15]:

1. By reference points

The most common way to register scans is using reference points with known coordinates of scanner reference marks located in the field of view of the scanner. During the execution of the scanner survey, the mire data are coordinated by the scanner at each station in a conditional coordinate system (scanner coordinate system), as well as from the points of completion survey using an electronic distance-measuring tachometer.

RiSCAN PRO software implements an approach in which the connections between reference marks are determined automatically by the geometry of the constellation. The result is expressed as a Table showing pairs of identical mires and discrepancies between the mire coordinates in both coordinate systems (Fig. 6).



Name	RefCount	RefType	Size	X	Y
SP10	1		0.00	6559...	4787...
SP11	1		0.00	6559...	4787...
SP2	1		0.00	6562...	4787...
SP3	1		0.00	6561...	4787...
SP4	1		0.00	6561...	4787...
SP5	1		0.00	6561...	4787...
SP7	1		0.00	6560...	4787...
SP8	1		0.00	6559...	4787...
SP9	1		0.00	6559...	4787...

Units: [deg] [m] 9 tiepoints, 1 selected Global coordinate system (GLCS)

Corresponding tiepoints: 9
Standard deviation [m]: 0.0781
Avg. radial deviation [m]: 0.0000
Avg. theta deviation [m]: -0.0150
Avg. phi deviation [m]: -0.0361

acc. Y	acc. Z	Height	σ X	σ Y	σ Z	mean X	mean Y	mean Z	Δ X	Δ Y	Δ Z
n.v.	n.v.	0.000	0.000	0.000	0.000	0.150	0.000	0.000	-0.007	0.076	-0.045
n.v.	n.v.	0.000	0.000	0.000	0.000	0.000	0.500	0.000	-0.054	-0.045	-0.023
n.v.	n.v.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.127	0.073	0.121
n.v.	n.v.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.116	0.134	-0.047
n.v.	n.v.	0.000	0.000	0.000	0.000	0.000	-0.400	0.000	0.094	0.049	-0.053
n.v.	n.v.	0.000	0.000	0.000	0.000	0.220	0.000	0.000	-0.003	-0.076	-0.071
n.v.	n.v.	0.000	0.000	0.000	0.000	0.200	0.500	0.000	-0.067	-0.003	0.092
n.v.	n.v.	0.000	0.000	0.000	0.000	-0.200	0.000	0.000	-0.072	-0.012	0.015
n.v.	n.v.	0.000	0.000	0.000	0.000	-0.200	-0.400	0.000	0.036	0.004	0.011

Fig. 6. Table of identical reference marks

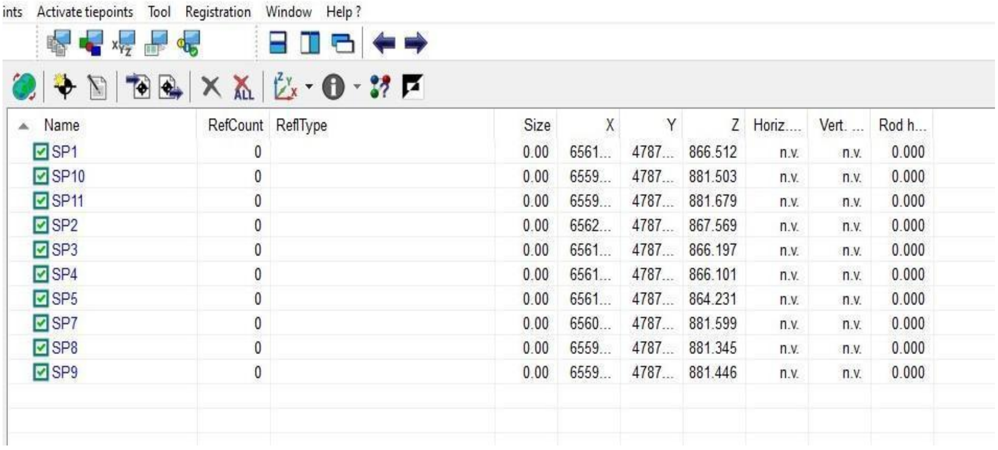
The accuracy of the reference marks position measured using a ground-based laser scanner relative to the external coordinate system is estimated by the discrepancy between the coordinates of the reference marks in both systems, or errors in determining linear and angular orientation elements.

2. By scans' overlapping

This method is based on the search and comparison of common objects in the areas of overlapping scans. This can be done employing a special Multi-Station Adjustment module in RiSCAN PRO software. According to the results of equalization, the software issues a report that contains information about the number of objects, the average square error of their relative position, and the distribution of errors in direction and magnitude

3 RESULTS AND DISCUSSIONS

Recall that the purpose of the present study is using advanced geodetic technologies, including a laser scanner to determine the optimal approach and working method for the allocation, quantification, and monitoring of building surfaces. The input data were three-dimensional coordinates of points, coordinates of points (X,Y,Z), line lengths (d), and angles between surfaces (θ) obtained by formula (Eq. 1) for the method under study (Fig. 7).



Name	RefCount	ReflType	Size	X	Y	Z	Horiz....	Vert. ...	Rod h...
☑ SP1	0		0.00	6561...	4787...	866.512	n.v.	n.v.	0.000
☑ SP10	0		0.00	6559...	4787...	881.503	n.v.	n.v.	0.000
☑ SP11	0		0.00	6559...	4787...	881.679	n.v.	n.v.	0.000
☑ SP2	0		0.00	6562...	4787...	867.569	n.v.	n.v.	0.000
☑ SP3	0		0.00	6561...	4787...	866.197	n.v.	n.v.	0.000
☑ SP4	0		0.00	6561...	4787...	866.101	n.v.	n.v.	0.000
☑ SP5	0		0.00	6561...	4787...	864.231	n.v.	n.v.	0.000
☑ SP7	0		0.00	6560...	4787...	881.599	n.v.	n.v.	0.000
☑ SP8	0		0.00	6559...	4787...	881.345	n.v.	n.v.	0.000
☑ SP9	0		0.00	6559...	4787...	881.446	n.v.	n.v.	0.000

Fig. 7. Input data

The general conditions for placing a ground-based lidar are capturing maximally geospatial information to form a complete point model, ensuring direct visibility to special scanner marks (if used), and striving to minimize the presence of dead zones. The choice of the scanner height should ensure that the maximum area of the territory being photographed is displayed on a single scan with the necessary detail. The maximum implementation accuracy is achieved by reflecting marks with known coordinates and obtaining at least four accurate scans of each mark (Fig. 8) [11, 12, 13, 15].

During the shooting of the object, eleven scan positions were set to obtain a 3D array; however, during the processing in the RiSCAN PRO software, it turned out, that eight scan positions were enough.

Fig. 8. Using a high-precision 3D laser scanner RIEGL VZ-4000 on the scanned area for maximum capture of the territory

The main principle of constructing the scanner travel path is that starting from the second station, three marks displayed on the first scan, and a minimum of three marks that will be visible from the third station, must fall into the field of view of the scan.

Stage, associated with GLS of the object includes the installation and horizontal positioning of the device, selection of the necessary parameters, and lidar operation modes (area, step, and scan mode) [2, 17].

Horizontal positioning of the station should be performed for models of ground-based laser scanners that are not equipped with a vertical axis tilt compensator.

Setting the scanning area for lidar is performed to install sectors, limited to the vertical and horizontal angles of the survey, as well as providing data collection on the object surface and the marks of the geodetic control with the necessary detail.

Three-dimensional modeling based on the results of the GLS can be performed directly using point clouds by inserting elements into them or using orthoimages. Besides, to obtain a reliable model, namely, a computer duplicate of the object under study, these methods can complement each other.

The efficiency of performing tasks related to monitoring the technical condition of high-rise buildings can be increased by creating special hardware and software tools. At that, such complexes should be maximally convenient and understandable to the user.

The main problem of monitoring the technical condition of high-rise objects using the technology in question is not so much the surveying process, which is fully automated, as the method of processing obtained results. It is necessary either to use a three-dimensional point model or to move from it to such a representation of the object that would allow solving the problems of considering deformations. Such representations can be flat (two-dimensional) and three-dimensional models of objects [6, 8, 12].

Monitoring of the object under study using the ground-based laser scanner was carried out twice, in August 2020 and September 2021. According to the results of two surveys, 3D images of the KazNU building were obtained. Based on data obtained, it was concluded that the deviations and the load on the building are within the permissible norm, which confirms previous studies using traditional technology and monitoring techniques (Fig. 9 a, b).

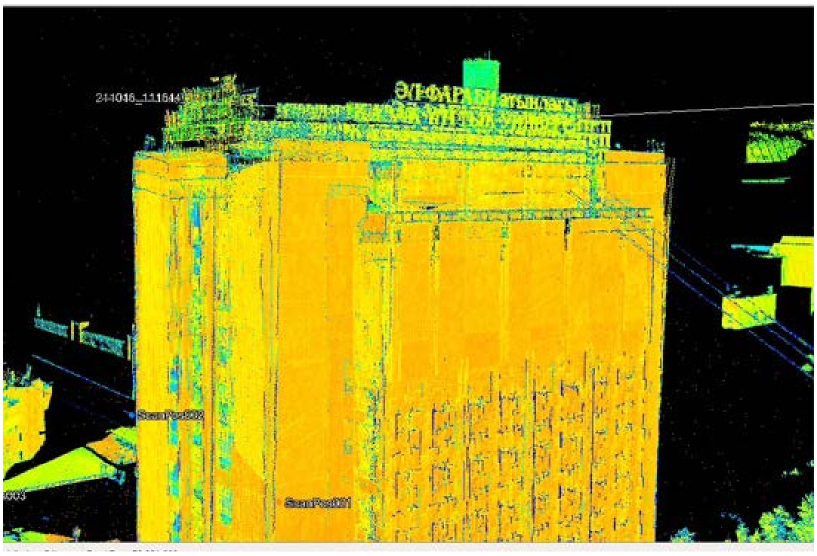


Fig. 9a. Results of a 3D image made in 2021

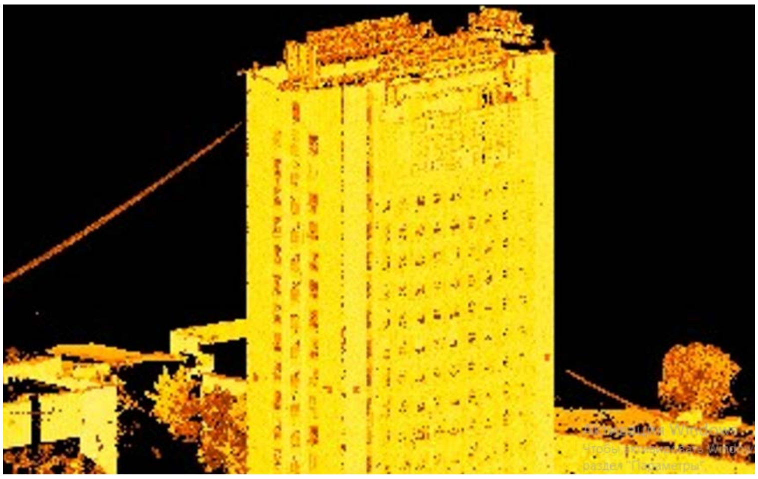


Fig. 9b. Results of a 3D image made in 2020

4 CONCLUSION

The article is devoted to the issues of monitoring the deformations of tower-type structures.

The article reflects all the main stages of field and cameral works. The authors studied the types of structure deformations, the instrumental observation process, and the method of calculating the results of observations.

Due to the design features, natural conditions, and human activity, structures in general, and their elements experience various kinds of deformations.

Based on the performed research, the authors solved the urgent scientific problem of developing a methodology for using the GLS technology to assess the deformation processes in the construction and operation of high-rise structures.

In high-rise buildings, deformations can occur on certain levels in the absence of deformation of the building footing. In terms of the deformation process, this is the main difference between a high-rise and low low-slung building.

When solving building deformation-related problems the main advantage of GLS is the high speed of work, high accuracy, non-contact method of data collection, completeness and detail of the acquired data, instant three-dimensional visualization, and the minimal influence of the human factor.

All stages of engineering and geodetic works were carried out using contemporary geodetic instruments and the newest software.

Due to the capabilities of RiSCAN PRO, the scan positions can be recorded directly in the field environment, which allows the operator to check the status of data acquisition and the extent of data coverage by constructing compact objects using point clouds and viewing their three-dimensional image.

Based on the results of two cycles of high-precision geodetic observations, it can be concluded that the results obtained have revealed minor deviations of the structure that can be explained by the effect of the specific geological, and hydrogeological conditions, as well as construction technology.

As the geodetic monitoring practice shows, the duration of the yield of the building foundation depends on the structure, lithological composition, and physical condition of the rocks that make up the foundations of the structures.

Besides, the results of monitoring are used to verify the correctness of design calculations and identify patterns that allow predicting the deformation process.

The performed work on observing the deformations of this structure allows us to continue the study using the reference and observation points established within the study object

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