UDC 622.830

M. B. NURPEISOVA[1], *Professor, Doctor of Engineering Sciences, marzhan-nurpessova@rambler.ru*
G. MEIRAMBEK[1], *Professor, Candidate of Engineering Sciences*
N. A. FEDOTENKO[2], *Senior Researcher, Candidate of Engineering Sciences*
B. T. ANETOV[1], *Doctoral Candidate*

[1]*Satbayev University, Almaty, Kazakhstan*
[2]*Academician Melnikov Research Institute of Comprehensive Exploitation of Mineral Resources–IPKON, Russian Academy of Sciences, Moscow, Russia*

A NEW APPROACH TO MONITORING DEFORMATION OF ENGINEERING STRUCTURES IN SEISMICALLY ACTIVE REGIONS

The article reports the Satbayev University's studies on deformation monitoring of engineering structures, in particular, the Abay Avenue/Saina Street interchange in the city of Almaty in the Republic of Kazakhstan. Almaty is situated in the region of increased seismic activity, including the main artery of the city–its subway that runs along the Abay Avenue. It is shown that the problem connected with safe operation of unique engineering structures can be solved using the integrated monitoring, encompassing all natural and manmade factors and their analysis, with the authorial procedure and equipment of geodetic surveying.

The research utilized an integrated approach, including: geological and geotechnical analyses of rock mass structure and tectonics, instrumental geodetic surveying with the use of GPS technologies, electronic tacheometry and ground-based scanning, as well as assessment of measurement accuracy.

The basic network deployment procedure is developed for the deformation monitoring of bridges, and geodetic monitoring of the test traffic interchange and above-ground buildings is performed. The use of electronic tacheometers and laser scanning with the satellite geodesy techniques in the geodetic monitoring is justified. For the installation of high-precision electronic and laser devices for the ground surface geomonitoring, the authors have designed a permanent station which provides fast and accurate centering without tripods. Based on the accomplished studies, the authors propose the subsidence and displacement determination methods for engineering structures. The research findings are included in a scientific project and in education and training courses.

The obtained results are usable in enhancement of industrial safety at other objects for the minimization of seismic risks in the region.

Keywords: *bridge, deformations, monitoring, base geodetic network, satellite-based positioning, electronic tacheometer, geodetic surveys, structural assessment*
DOI: *10.17580/em.2024.01.09*

Introduction

In the city of Almaty, many traffic intersections have been built in recent years, including the Abay Avenue/Saina Street interchange. This traffic intersection is situated in very specific geological and geotechnical conditions, in the influence zone of the strongest earthquakes in the northern Tian Shan. Furthermore, a subway is now being constructed along the Abay Avenue, in the east–west direction. The subway construction in Almaty features some geotechnical complexities, namely:

1. The seismic activity is very high in the city and reaches intensity of 9–10 on the MSK-64 scale;
2. The local terrain is inclined as it lies in the intermountain area;
3. The rock mass contains tectonic faults;
4. The depths of the subway tunnels and stations vary from shallow depths of 11 m to great depths of 60 m.

Despite these difficulties, Almaty is a rapidly developing city: its layout changes, new large engineering structures appear (traffic interchanges and long-distance bridges within the city limits), and the city itself expands. All these changes influence the size and loading of geological faults. Structural assessment and prediction of technical condition of engineering facilities being built and operated becomes especially acute in this case. A solution to this problem is geodetic monitoring.

The subject of research is the Abay Avenue/Saina Street interchange (**Fig. 1**).

Fig. 1. Abay Avenue/Saina Street interchange

Geological structure. Geomorphologically, the test area occurs within a piedmont slope running north from the Trans-Ili Alatau. Lithologically, the area is composed of alluvial–proluvial Late Pleistocene units representing gravel deposits overlaid with loess loam, seldom with sandy loam. To get details of the regional geology and lithology, 51 exploring shafts each 10.0–18.0 m long were drilled in the test area. The total drilling length was 806.0 m, including 49.0 m-long drilling in fill ground. Below, gravel deposits with sand up to 20–30% were intersected, slightly wet, with boulder stones up to 25–30% (in wells NN1;4;5;7;8;11;12 to the depth of 6.0–6.7 m, gravel deposits with loam). The exposed thickness of gravel deposits ranges as 4.9–14.2 m [1–3].

Seismicity of the construction area. The area of the traffic interchange is situated in the zone of the possible Almaty fault evidence, which is proved by archival data of the Kazakh Geotechnical Institute of Surveying (KazGII).

Figure 2 shows the map of earthquake epicenters for 2005–2020 and the tectonics of the Almaty neighborhood 60–70 km in size on the surface contour map. The map shows the epicenters of modern earthquakes, the epicenters of the strongest historical earthquakes with the magnitude 5.5 and higher, as well as the active faults [4].

Materials and methods

The research used an integrated approach including: geological and geotechnical analyses of structure and tectonics of rock mass, instrumental geotechnical survey using GPS technologies, an electronic tacheometer, surface scanning and measurement accuracy assessment.

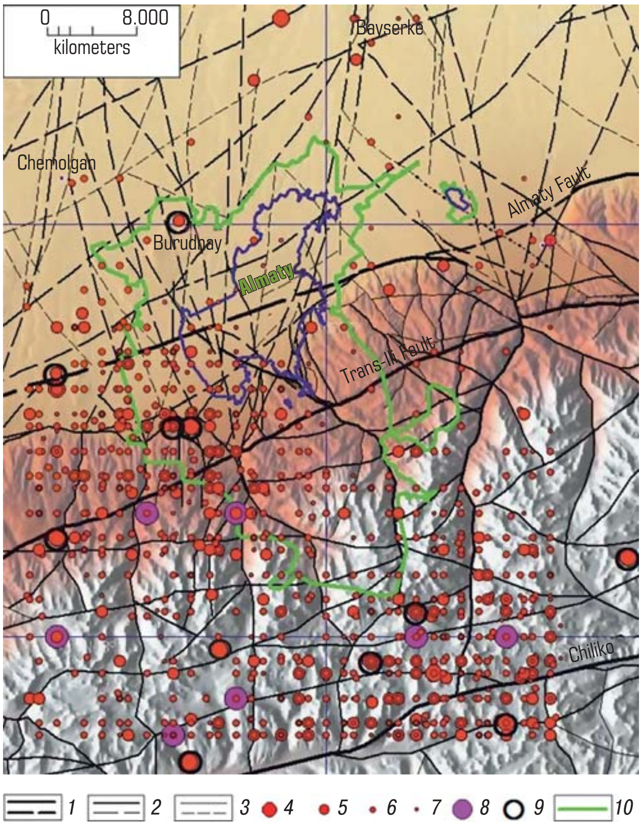

Fig. 2. Modern seismicity (2005–2020) and tectonics of the Almaty area 60–70 km on relief map

Tectonic faulting of parent rock mass and overlying loose deposits (dashed lines): *1* – primary faults; *2* – main faults; *3* – secondary faults. Epicenters of earthquakes with magnitude (mpv): *4* – from 4 to 4.7; *5* – from 3 to 4; *6* – from 2 to 3; *7* – up to 2; *8* – epicenters of strong historical earthquakes with magnitude 5.5 and higher; *9* – epicenters of sensible earthquakes with strong displacements recorded after 2005; *10* – limits of Almaty by 2015

Construction of traffic intersections, bridges and any other structures requires a base geodetic network. The base geodetic networks are used to identify and assign positions for the centers of bridge piers and other bridge members, to perform detailed laying out when erecting bridge piers and bridge spans, as well as to monitor deformations of the structures.

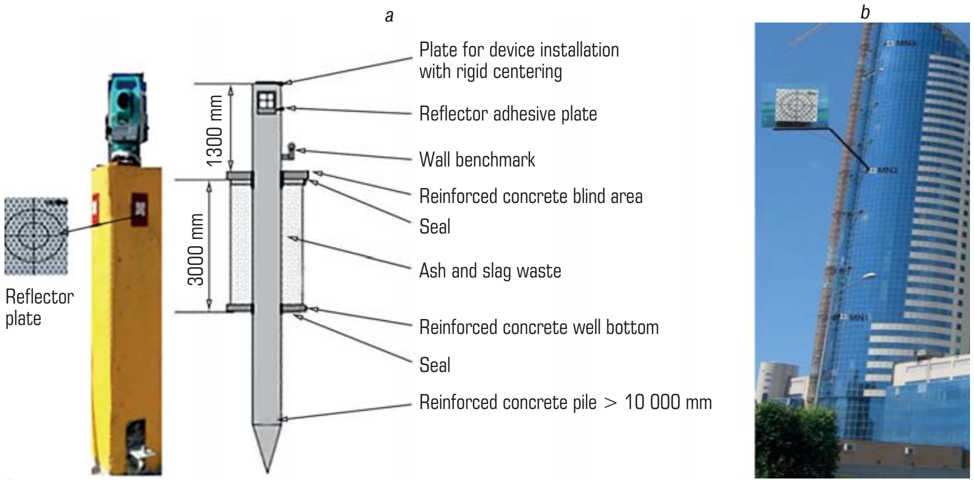

Fig. 4. Schematic geodetic pile (*a*) and reflector plates (*b*)

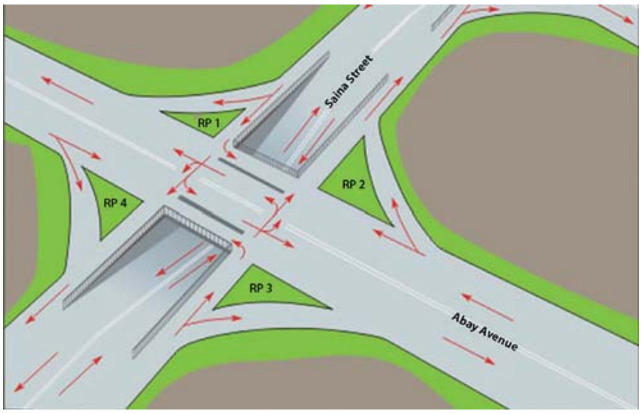

Fig. 3. Arrangement of survey control points in traffic interchange network

A geodetic network of bridge construction engineering should be created in a uniform coordinate system and should provide extra accuracy of positioning. The geodetic network points, which ensure construction of an object as a unit piece, should stand for the whole period of construction. This is a not easy task as some geodetic points get eliminated or broken down in the course of construction [5].

To implement monitoring, the Geodesy and Surveying Department of the Satbayev University developed a project of a geodynamic testing site (GTS) in 2020 using GNSS, with the survey control points arranged with regard to the configuration of the objects being supervised (**Fig. 3**). The work was accomplished using modern equipment and control facilities [6].

The main components of the proposed geodetic network are:

The first order network—survey control points (SCP) of permanent geodetic stations coordinated with the State Geodetic Network, with a forced centering device (RP1–RP4 in Fig. 3). The adopted height of the points is not less than 1.5 m to eliminate any obstacles to RF signal passage.

The second order network—points of the satellite geodesy network (SDN) on the body of an object under supervision.

The check points are laid on the foundations of buildings and structures along the street. On the objects being supervised, the reflector and seismic plates, monitoring prisms and subsidence markers are set to observe deformations of the test objects at the accuracy as per the effective standards [7, 8].

In monitoring deformations of the traffic interchange and high-rise buildings, for the permanent points, a new design of the geodetic points with forced centering was proposed in conformity with the normative standards [10]. The geodetic point with forced centering represents a reinforced concrete pile 12 m long (**Fig. 4**) installed at the selected location.

Robustness of the points is readily controlled via repeated measurements. The accuracy of the relative position of the points is improved using *trilateration*.

Creation of the geodetic piles should observe the following requirements. The height of the pile should exceed the planned levelling operations involved in site improvement by 1.3 m approximately, and should be placed vertically using braces and jacking frames. To install the casing of a pile with a diameter of 0.6 m, a hole not less than 3.4 m long is drilled. To ensure steadfastness of the pile, the bottom hole is compacted and filled with a concrete layer 50 mm thick. Then, a casing tube with a diameter of 0.5 and length of 3 m is set on the concrete layer so that the pile occurs in the center of this structure. To eliminate the impacts of temperature and rainfalls, a top layer of ash and slag waste is made with the subsequent sheathing and armoring. To install a geodetic device, a plate 0.2×0.2 m with a set screw is arranged on the top of the pile. To ensure visibility in all directions, rectangular metal plates with adhesive reflector plates are fixated on all sides of the pile [10, 11].

The new device improves accuracy of centering and flexibility of measurements without tripods set at the points of standing and observation.

For obtaining accurate coordinates for the compilation survey, it was decided to use GNSS equipment. Satellite measurements were performed in the mode "Statics", which involved two conventional stages, namely, field work and office study.

The geodetic monitoring of industrial infrastructure facilities aims to provide: reliability, safety and serviceability of operating structures; analysis of stresses, strains and displacements; observations over general deformations and cracking in certain components of an operating structure by means of systematic surveillance and instrumental control.

The monitoring takes into account all critical geological and geotechnical factors, types and characteristics of the guarded objects and the requirements imposed on them [12–14].

All works were executed using GPS systems, the results were compared using Leica Geosystem TCR1201 electronic tacheometer, DNA03 high-precision digital level and a laser scanner. The geodetic base coordinates were determined in the local system, and the ground elevations were determined from the Baltic Height System.

The vertical displacements (subsidence) of the structures were assessed from the geodetic levelling using DNA03 level and a digital invar levelling rod. Tilting of the bridge columns was estimated using coordinates from the electronic tacheometer. Using the obtained values and increments of coordinates of the points lying in the same vertical plane, the linear values of the tilt are calculated from the formula:

$$L = \sqrt{\left(X_1 - X_2\right)^2 + \left(Y_1 - Y_2\right)^2}, \tag{1}$$

where X_1, X_2, Y_1, Y_2 are the coordinates of the representative points in the lower and upper section of a structure.

Eccentricity of circular bridge pillars was determined from the points of the geodetic network. Deflection of the floor beams of the bridge was evaluated using the high-precision digital level and invar levelling rod. The rod was installed at the beginning, middle and end points of each beam span.

The absolute and relative values of deflection, f_{abs} (**Fig. 5**) and f_{rel}, respectively, are found from the formulas:

$$f_{abs} = \frac{2Z_2 - \left(Z_1 + Z_3\right)}{2}; \tag{2}$$

$$f_{rel} = \frac{f_{abs}}{L}, \tag{3}$$

where Z_1 and Z_3 are the heights of the extreme points of a structure in the test section of a straight line.

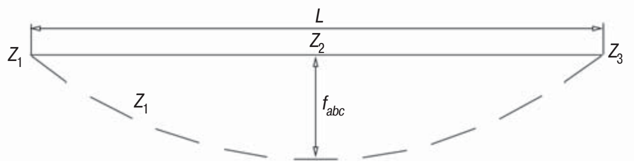

Fig. 5. Layout of deflection of floor beams

The structural assessment results obtained using the described procedure were compared with the allowable values as per construction norms and regulations [15]. The allowable deflection of the floor beams is 1/300 L, where L is the beam length, m. The allowable deflection for the bridge columns is 15 mm at their height up to 4 m.

Conclusions

Geodetic observations over deformations of structures should meet the required completeness, promptness and accuracy. In this respect, creation of a monitoring network for the high-precision surveillance over engineering structures using electronic and GPS devices made it possible to save the time of positioning per a point by 10–15 times and to increase the positioning accuracy not less than by 2 times.

Acknowledgements

This study was supported by the Ministry of Science and Higher Education of the Republic of Kazakhstan, Grant No. AP23489269 Geotechnical Monitoring of Geodynamics of Geological and Structural Environment in Rock Mass during Subsoil Development towards Industrial Reliability.

References

1. Nusipov E. Geoinformation Technologies and Integrated Geological and Geophysical Analysis. Almaty : Gylym, 2001. 306 p.
2. Medeu A., Blagovechshensky V., Zhdanov V., Ranova S. Assessment and mapping of landslide risk In the territory of Almaty city. *News of the National Academy of Sciences of Kazakhstan. Series of Geology and Technical Sciences*. 2018. No. 1. pp. 34–41.
3. Erzhanov Zh. S., Shatsilov V. I., Nurmagambetov A. et al. Seismic Microzoning of the Almaty City Area. Almaty : Nauka, 1982. 111 p.
4. Nurpeisova M., Kartbayeva K., Huayang D. et al. Experience of Geodesic Observations In Almaty Geodynamic Polygon. *JARDCS*. 2019. Vol. 11. pp. 2068–2074.
5. Zhukov B. N., Karpik A. P. Geodetic Control of Engineering Facilities at Industrial Plants and Civil Structures. Novosibirsk : SGGA, 2006. 147 p.
6. Kyrgizbayeva G. M., Nurpeisova M. B. A New Approach to Creation of a Geodynamic Test Site. Copyright State Registration Certificate RK. No. 20302. Published: 17.09.2021.
7. Available at: https://ohranatruda.ru/upload/iblock/23c/4294854742.pdf (accessed: 26.09.2024).
8. Available at: https://kazgeosfera.kz/wp-content/uploads/2018/05/%D0%A1%D0%9D%D0%98%D0%9F-%D0%A0%D0%9A-1.03-26-2004.pdf (accessed: 26.09.2024).
9. Regulations on Assessment and Maintenance of Artificial Structures at Railways in the Republic of Kazakhstan. Almaty, 1998.
10. Nurpeisova M. B., Rysbekov K. B., Aitkazinova Sh. K. et al. Ground Permanent Geodetic Point with Forced Centering. Patent RK, No. 35798. Published: 19.08.2022.
11. Nurpeisova M. B., Bitimbayev M. Zh., Rysbekov K. B., et al. Seismic Method of Stress–Strain Prediction in Rock Mass. Patent RK, No. 35898. Published: 14.10.2022.
12. Available at: https://zan.kz/ru/Document/DetailById?documentId=abfe7193-e5f6-4f03-9448-37db30eaa264 (accessed: 26.09.2024).
13. Available at: https://continent-online.com/Document/?doc_id=30399772#pos=0;0 (accessed: 26.09.2024).
14. Bazaluk O., Rysbekov K., Nurpeisova M. et al. Integrated Monitoring for the Rock Mass State During Large-Scale Subsoil Development. *Frontiers in Environmental Science*. 2022. Vol. 10. ID 852591.
15. Available at: https://kazib.kz/downloads/regulations/Obsledovnie_i_ocenka_tech_sostoyaniya_zdaniy_i_sooruzheniy_CH_RoK_1.04-04-2002.pdf (accessed: 26.09.2024).