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RESEARCH ARTICLE

MONITORING DEFORMATIONS OF ENGINEERING STRUCTURES IN SEISMIC REGIONS

D. Kirgizbayeva[1], M. Nurpeisova[1], K. Menayakov[1], T. Nurpeisova[1], A. Umirbayeva[2,*]

[1]Satbayev University, 050013, Almaty, Kazakhstan
[2]International Educational Corporation, 050028, Almaty, Kazakhstan

Abstract. *The article considers the issues of ensuring the safety of operation of engineering structures in seismically hazardous regions, using the example of the transport interchange of Abay Avenue and Sain Street in Almaty, Republic of Kazakhstan. Almaty is located in a zone of increased seismic activity, and a metro line runs along Abay Avenue, which complicates the engineering and geological situation. In such cases, the creation of an effective system for monitoring the condition of structures is of particular importance. An integrated approach is proposed, including an engineering and geological study of the rock massif, satellite GPS technologies, an electronic tacheometer, laser scanning of the earth and an assessment of the accuracy of geodetic measurements. A methodology for constructing a reference geodetic network for monitoring bridges and buildings has been developed. The expediency of using satellite positioning, tacheometry and scanning when monitoring deformations and settlements of structures is substantiated. To install high-precision electronic and laser devices for geomonitoring the earth's surface, the authors have developed a permanent point that ensures speed and accuracy of centering, eliminating the use of tripods. Based on the conducted research, the authors propose methods for determining the settlements and displacements of structures. The results of the research were implemented in the implementation of a scientific project, and also used in the educational process. The practical value of the work lies in the possibility of using the obtained results to improve the level of safety at similar facilities and reduce the risks associated with natural and man-made factors.*

Keywords: *bridge, deformations, monitoring, geodetic reference networks, satellite positioning, geodetic observations, technical condition assessment.*

***Corresponding author**
Aliya Umirbayeva, e-mail: a.umirbaeva@mok.kz

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ҒЫЛЫМИ МАҚАЛА

СЕЙСМИКАЛЫҚ АЙМАҚТАРДАҒЫ ИНЖЕНЕРЛІК ҚҰРЫЛЫСТАРДЫҢ ДЕФОРМАЦИЯЛАРЫН БАҚЫЛАУ

Д.М. Киргизбаева[1], М.Б. Нурпеисова[1], К.Т.Менаяков[1], Т.Б. Нурпеисова[1], А.Б. Умирбаева[2,*]

[1]Сәтбаев Университеті, 050013, Алматы, Қазақстан
[2]Халықаралық білім беру корпорациясы, 050028, Алматы, Қазақстан

Аңдатпа. *Мақалада сейсмикалық қауіпті өңірлерде инженерлік құрылыстарды пайдалану қауіпсіздігін қамтамасыз ету мәселелері, Қазақстан Республикасы, Алматы қаласындағы Абай даңғылы мен Саин көшесінің көлік айрығы мысалында қарастырылған. Алматы қаласы сейсмикалық белсенділігі жоғары аймақта орналасқан, ал Абай даңғылының бойында Метрополитен сызығы өтеді, бұл инженерлік-геологиялық жағдайды қиындатады. Мұндай жағдайларда құрылыстардың жай-күйін бақылаудың тиімді жүйесін құру ерекше маңызға ие. Тау жыныстарының массивін инженерлік-геологиялық зерттеу, спутниктік GPS технологиялары, электронды тахеометр, жерді лазерлік сканерлеу және геодезиялық өлшеулердің дәлдігін бағалауды қамтитын кешенді тәсіл ұсынылды. Көпірлер мен ғимараттарды бақылау үшін тірек геодезиялық желіні құру әдістемесі жасалды. Құрылыстардың деформациялары мен жауын-шашындарын бақылау кезінде спутниктік позициялауды, тахеометрияны және Сканерлеуді қолданудың орындылығы негізделген. Жер бетін геомониторинг кезінде жоғары дәлдіктегі электронды және лазерлік Аспаптарды орнату үшін авторлар штативтерді қолдануды болдырмай, орталықтандырудың жылдамдығы мен дәлдігін қамтамасыз етуге мүмкіндік беретін тұрақты пункт әзірледі. Зерттеу негізінде авторлар құрылымдардың шөгінділері менмещысуларын анықтау әдістерін ұсынады. Зерттеу нәтижелері ғылыми жобаны орындау кезінде енгізілді, сонымен қатар оқу процесінде қолданылды. Жұмыстың практикалық құндылығы ұқсас объектілердегі қауіпсіздік деңгейін арттыру және табиғи-техногендік факторлармен байланысты тәуекелдерді азайту үшін алынған нәтижелерді қолдану мүмкіндігі болып табылады.*

Түйін сөздер: *көпір, деформациялар, мониторинг, геодезиялық тірек желілер, спутниктік позициялау, геодезиялық бақылаулар, техникалық жағдайды бағалау.*

***Автор-корреспондент**
Умирбаева А.Б., e-mail: a.umirbaeva@mok.kz

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НАУЧНАЯ СТАТЬЯ

НАБЛЮДЕНИЕ ЗА ДЕФОРМАЦИЯМИ ИНЖЕНЕРНЫХ СООРУЖЕНИЙ В СЕЙСМИЧЕСКИХ РЕГИОНАХ

Д.М. Киргизбаева[1], М.Б. Нурпеисова[1], К.Т. Менаяков[1], Т.Б. Нурпеисова[1], А.Б. Умирбаева[2,*]

[1]Университет Сатпаева, 050013, Алматы, Казахстан
[2]Международная образовательная корпорация, 050028, Алматы, Казахстан

Аннотация. *В статье рассмотрены вопросы обеспечения безопасности эксплуатации инженерных сооружений в сейсмоопасных регионах, на примере транспортной развязки проспекта Абая и улицы Саина в городе Алматы, Республика Казахстан. Город Алматы расположен в зоне повышенной сейсмической активности, а вдоль проспекта Абая проходит линия метрополитена, что усложняет инженерно-геологическую ситуацию. В таких случаях особое значение имеет создание эффективной системы контроля за состоянием сооружений. Предложен комплексный подход, включающий инженерно-геологическое изучение массива горных пород, спутниковые GPS-технологии, электронный тахеометр, лазерное сканирование земли и оценку точности геодезических измерений. Разработана методика построения опорной геодезической сети для наблюдения за мостами и зданиями. Обоснована целесообразность применения спутникового позиционирования, тахеометрии и сканирования при наблюдении деформаций и осадков сооружений. Для установки высокоточных электронных и лазерных приборов при геомониторинге земной поверхности, авторами, разработан постоянный пункт, позволяющий обеспечить быстроту и точность центрирования, исключив применения штативов. На основе проведенного исследования авторами предлагаются методы определения осадок и смещений сооружений. Результаты исследовании внедрены при выполнении научного проекта, а также использованы в учебном процессе. Практическая ценность работы заключается в возможности применения полученных результатов для повышения уровня безопасности на аналогичных объектах и снижения рисков, связанных с природно-техногенными факторами.*

Ключевые слова: *мост, деформации, мониторинг, опорные геодезические сети, спутниковое позиционирование, геодезические наблюдения, оценка технического состояния.*

***Автор-корреспондент**
Умирбаева А.Б., e-mail: a.umirbaeva@mok.kz

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің IRN AP23489269 «Өнеркәсіптік сенімділікті қамтамасыз ету үшін жер қойнауын игеру кезінде тау жыныстары массивінің геологиялық-құрылымдық ортасының геодинамикалық жай-күйінің геотехникалық мониторингі» гранттық қаржыландыру шеңберінде жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось в рамках грантового финансирования Комитета науки Министерства науки и высшего образования Республики Казахстан IRN AP23489269 «Геотехническое мониторирование геодинамического состояния геолого-структурной среды массива горных пород при освоении недр для обеспечение промышленной надежности».

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

In recent years, many transport interchanges have been built in the city of Almaty, one of them is the intersection of Abay Avenue and Saina Street.Almaty is located in specific engineering and geological conditions and is in the zone of influence of the strongest earthquakes of the Northern Tien Shan. In addition, from east to west along Abay Avenue, a subway is being built. The peculiarity of the construction of the subway in the city of Almaty is that it has a number of complex geotechnical factors, which are:

1. Seismic activity in the city is very high and reaches 9-10 points on the MSK-64 scale.
2. The relief is sloping, as it is located in the area of an intermountain depression.
3. The presence of tectonic faults.
4. The depths of station tunnels and transfer stations vary; there are shallow areas from 11 meters and deep components of 60 meters.

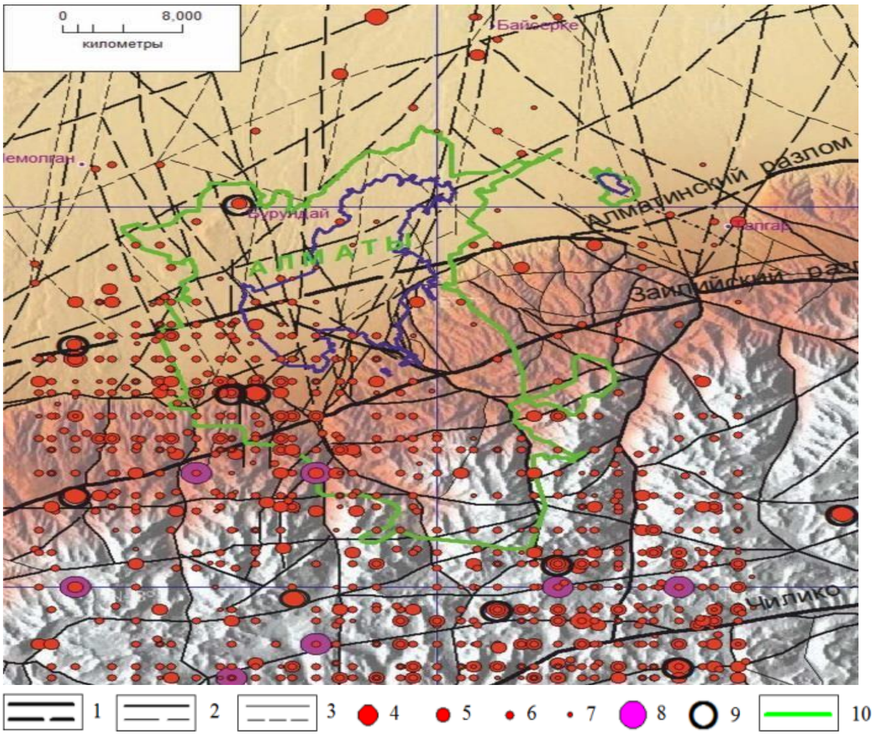
Despite such difficult conditions, andintensive development of the city of Almaty,expressed in changes in its layout, the emergence of new large engineering structures, such as transport interchanges and long bridges within the city limits, the expansion of boundaries affects the size and load of geological faults. In these conditions, the problem of forecasting the technical condition of buildings under construction and in operation becomes acute. Its solution is provided by geodetic monitoring. The object of the study is the transport interchange at the intersection of Abay Avenue and Saina Street (**Figure 1**).

Figure 1 – Transport interchange along Abay Avenue – Saina Street.

*Geological structure.*In geomorphological terms, the site under survey is located within the foothill sloping plain extending north from the foothills of the Zailiyskiy Alatau. Alluvial-proluvial Upper Quaternary deposits participate in the geological and lithological structure of the site. In lithological terms, they are represented by pebble soils overlain by loess-like loams, rarely by sandy loams. For detailing the geological and lithological section, 51 test boreholes, 10.0-18.0 m deep each, were drilled on the site. A total of 806.0 running meters were drilled, including 49.0 m by test boreholes (on bulk soils). Below, pebble soils with sand filler up to 20-30%, low-moisture, with inclusion of boulders up to 25-30%, are exposed (in wells NN1; 4; 5; 7; 8; 11; 12 to a depth of 6.0-6.7 m pebble soils with loamy filler). The exposed thickness of pebble soils is 4.9-14.2 m. **(Nusipov E. et al., 2001), (Medeu A. et al., 2018)**.

*Engineering and seismic conditions of the construction site.*The site of the transport interchange is located in the zone of possible manifestation of the Almaty tectonic fault, which is confirmed by the results of the archive materials of the Kazakh Geotechnical Research Institute (KazGII).

On **Figure 2** the map of earthquake epicenters for 2005-06.2020 and the tectonics of the Almaty region in a 60x70 km contour on a topographic map are presented. In addition to the epicenters of modern earthquakes, the map shows the epicenters of strong earthquakes from historical times with a magnitude of 5.5 or more, as well as active faults (**Nurpeisova M. et al., 2021**).



Tectonic faults in bedrock and overlain by loose sediments (dotted line): 1 – main 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 earthquakes since historical times with magnitude 5.5 and more; 9 – Epicenters of perceptible earthquakes after 2005 with records of strong movements; 10 – contour of Almaty city in 2015.

Figure 2 – Modern seismicity (2005-2020) and tectonics of the Almaty region in a 60x70 km contour on the relief map.

In accordance with this position, the goal was set, the idea was substantiated, and the research objectives were formulated.

2 LITERATURE REVIEW

Ensuring the safety of engineering structures located in seismically active zones requires the use of modern geomonitoring technologies capable of tracking spatial displacements and deformations of structures with high accuracy. One of the most common methods is satellite positioning using GNSS systems. **(Zhang et al., 2023)** discusses the possibilities of GNSS monitoring to control deformations of structures, especially in a complex geodynamic environment. The authors emphasize the effectiveness of RTK and static survey modes for measuring displacements within sub-centimeter accuracy, which is especially important when monitoring objects in dense urban areas and increased seismic activity **(Wu et al., 2021)**. An integrated approach combining GNSS and traditional geodetic methods is actively used in modern monitoring systems. Thus, **(Fan et al., 2024)** emphasize the need to use total station observations in combination with leveling to obtain objective data on vertical and horizontal displacements of structures. This is especially important when monitoring transport infrastructure facilities, where there is a high probability of uneven precipitation and deformations. The use of ground-based laser scanning (TLS) is of great importance in modern research, which makes it possible to obtain detailed point clouds and detect deformations with millimeter accuracy. **(Singh et al., 2023)** demonstrate the effectiveness of TLS in monitoring retaining walls and other engineering structures, where geometric accuracy and 3D visualization are key to assessing technical condition. Additional studies by **Bertacchini and Castagnetti (2012)** confirm the high informative value of TLS for spatial analysis of deformation processes, especially during repeated observations of the dynamics of displacement of structural elements. The integration of laser scanning with GPS measurements provides comprehensive data on the movement of structures. **(Teng et al., 2024)** describe a combined approach in which TLS is complemented by DGPS, which makes it possible to link point clouds to a single coordinate system and perform high-precision deformation analytics based on spatial and temporal models. A separate area in geomonitoring is the application of satellite radar interferometry (InSAR) methods. **(Okiemute et al., 2018)** studied precipitation in the urban area of Almaty using SBAS-InSAR, identifying zones of deformation activity correlating with engineering and geological conditions. Frontiers in Built Environment also demonstrates the high accuracy of the method for tracking spatiotemporal changes in urbanized areas and in the analysis of anthropogenic factors. Domestic research, in particular the work of **Urazbaev et al. (2021)**, demonstrates the successful implementation of geodetic methods for monitoring the technical condition of structures in Kazakhstan. The authors focus on the creation of geodetic reference networks and the use of high-precision electronic total stations and GNSS receivers for monitoring bridges, buildings and transport interchanges in conditions of difficult soils and seismic mobility of the territory.

Thus, the analysis of existing sources confirms the relevance and scientific validity of an integrated approach to geomonitoring, including satellite positioning, electronic total station, ground-based laser scanning and the creation of stationary geodetic points. The combined use of these technologies makes it possible not only to reliably assess current deformation processes, but also to form an effective emergency prevention system for engineering structures in earthquake-prone regions.

3 MATERIALS AND METHODS

The study was conducted using the example of the transport interchange of Abai Avenue and Sain Street in Almaty, located in a zone of increased seismic activity. Considering the difficult engineering and geological situation caused by the presence of a metro line along the avenue, an integrated approach was implemented, including several stages of geomonitoring using modern geodetic technologies. At the first stage, engineering and geological surveys were carried out to assess the structural and tectonic structure of the rock mass. The physico-mechanical properties of soils were studied, groundwater levels were determined, and possible faults and areas of increased mobility were recorded. The field survey data formed the basis for constructing a model of the engineering and geological situation of the site under study. The next stage was the creation and consolidation of the geodetic reference network. To improve the accuracy of observations, the authors have developed stationary observation points that allow the installation of high-precision electronic and laser devices without using tripods, which eliminates errors associated with centering errors. The coordinates of the points were determined using satellite geodesy (GNSS) in static mode followed by post-processing of the data. Geodetic monitoring was carried out using the following instrumental methods:

• Satellite positioning (GNSS): dual-frequency receivers were used in static and kinematic imaging (RTK) mode, which ensured high accuracy in determining the spatial coordinates of control points on observation objects.

• Electronic total station: used for detailed measurement of horizontal and vertical displacements of structures. The measurements were carried out using fixed reflectors on the elements of the bridge structure.

• Ground-based laser scanning (TLS): used to obtain three-dimensional information about the shape and position of structures. Point clouds obtained in different periods were compared for visualization and quantification of deformations **(Batilovic et al., 2024)**.

• Accuracy assessment: at each stage, the metrological characteristics of the measurements were evaluated, the standard deviations were calculated, and the consistency of the results between the methods was monitored. Additionally, a methodology for calculating precipitation and displacement based on the integration of GNSS, total station and TLS data has been developed **(Soilan et al., 2019)**. The development includes an algorithm for processing time series of measurements, a comparison of geometric parameters of structures for different eras of observations, as well as recommendations on the intervals of repeated measurements. The implementation of this geomonitoring system was implemented as part of a scientific project and used in the educational process of training specialists in the field of geodesy. The use of an integrated approach has allowed not only to improve the accuracy and reliability of observations, but also to create the basis for regular technical monitoring of similar facilities in earthquake-prone regions.

4 RESULTS AND DISCUSSION

Construction of interchanges, bridges, as well as construction of any other structures, requires the creation of a reference geodetic network. Using reference geodetic networks, the position of the centers of bridge supports and other elements of the bridge is determined and fixed, a detailed breakdown is made during the construction of supports and installation of span structures, and observations of deformations of structures are carried out. The geodetic network during bridge construction must be created in a single coordinate system and have increased accuracy in determining the coordinates of points. Geodetic network points that ensure the construction of a given object as a single structure must exist during the construction of the object. This requirement is not easy to fulfill, since during construction, some of the geodetic network points are destroyed or violated.

For monitoring by the Department of Mine Surveying and Geodesy SatbayevUniversity drafted a geodynamic testing area (GTA) project in 2020in the form of a GNSS network, where reference points are located considering the configuration of the observed objects (**Figure 3**). An important aspect in carrying out these works was the use of modern instruments and developed control tools for monitoring.

The main elements of the proposed geodetic network are:

First order network - is designed in the form of reference points (OP) of permanently operating geodetic base stations with reference to the State Geodetic Network (SGN) with a forced centering device (OP 1, OP2, OP 3, OP 4). The height of the points is taken to be not less than 1.5 m, to avoid obstacles to the passage of the radio signal.

The second-order network is designed in the form of points of the first-order satellite geodetic network (SGN) on the body of the observed objects.

Figure 3 – Layout of the support points of the transport interchange network.

Control points are laid along the street on the foundations of buildings and structures. Reflective and seismological marks, monitoring prisms and sedimentary marks are fixed on the controlled objects, along which further observations of deformations of buildings and structures are carried out, ensuring the necessary accuracy in accordance with the requirements of SP RK 3.06.07-86 «Bridges and pipes». Rules for surveys and tests and SP RK 1.03-26-2004 «Geodetic works in construction».

When monitoring the deformation of a transport interchange and high-rise buildings, a new design of geodetic points of forced centering (GPCC) was proposed as permanent supports, which meets the standards of regulatory literature **(Patent No. 35798)**, **(Patent No. 35898).** GPCC is a reinforced concrete pile, 12 meters long (**Figure 4**), installed in the selected location.

The stability control of the points can be easily performed by repeated measurements. The accuracy of determining the relative position of the starting points is increased by using the trilateration method.

When creating geodetic control points (GCPs), the following requirements must be met. The pile height must be approximately 1.3 m higher than the planned vertical layout of the landscaping, with its installation in a vertical position using spacers and jack frames. A hole at least 3.2 m deep is drilled around a pile with a diameter of 0.6 m to install the casing pipe. In order to ensure the stability of the pile, the bottom of the hole must be tamped and filled with concrete approximately 50 mm thick. After this, a casing pipe approximately 0.5 m in diameter and 3 m long is installed on the concrete, so that the pile is in the center of this structure. To eliminate the influence of temperature and rainfall, a layer of ash and slag waste is placed on top, followed by the construction of formwork and a blind area. To ensure the installation of a geodetic device, a table measuring 0.2 × 0.2 m with a set screw is mounted on top of the pile. In order to ensure visibility from all directions, on each rectangular metal plates are installed on the side of the pile, to which reflective plates are glued **(Patent No. 35898)**.

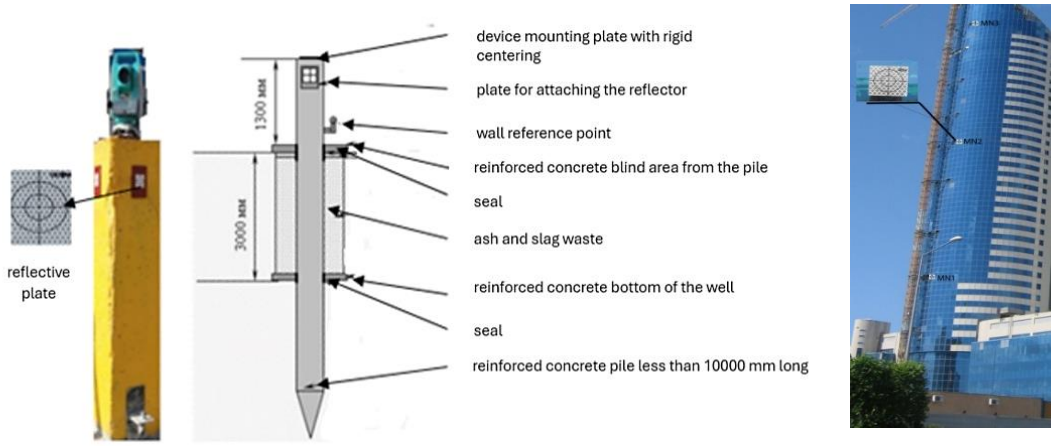


Figure 4 – Scheme of pile support point (a) and reflective observation marks (b).

The new device allows to increase the accuracy of centering, as well as the efficiency of measurements in the absence of tripods at the points of standing and observation. To obtain precise coordinates for the planned altitude justification of the network, it was decided to use GNSS equipment and satellite measurements that performed in static mode; work in this mode implies a conditional division into two stages, these are field work and office processing. The purpose of geodetic monitoring of industrial site structures is to ensure the reliability, safety and functional suitability of the structures in operation; analysis of the stress state, deformations and displacements of structures; observation of general deformations and cracks in individual elements of the structures in operation by conducting systematic observations and instrumental control.

When solving monitoring problems, all the most important engineering-geological and mining factors, the type and characteristics of the protected structures, and the requirements imposed on them were considered.

All work was carried out by the GPS system and for comparison of results the electronic tachometer TCR1201 from Leica Geosystem and the digital high-precision level DNA03 were used. Andlaser scanner. The coordinates of the geodetic base are defined in the local system, and the altitude coordinates are defined in the Baltic system.

The displacement of structures in the vertical plane (settlement) is determined by the geometric leveling method using a DNA 03 digital laser level and a digital invar rod. The determination of the roll of the bridge columns was carried out using coordinates using an electronic tacheometer. Based on the obtained values and increments of the coordinates of points located in the same vertical plane, the linear value of the roll was calculated using the formula:

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

where X1, X2, Y1, Y2 are the coordinates of the characteristic points of the structure in the lower and upper sections, respectively.

The determination of the eccentricity of the coaxiality of the circular bridge support was carried out from the points of the geodetic network, and the determination of the deflection of the bridge roof beams was carried out using a digital high-precision level and a digital invar rod. To solve this problem, the rod was installed at the points of the beginning, middle and end of each beam span.

To determine the deflection, the magnitude of the deflection arrow $f_{абс}$ and relative deflection $f_{отн}$ calculated using the formulas:

$$f_{абс} = \frac{2Z_2 - (Z_1 + Z_3)}{2}; \quad (2)$$

$$f_{отн} = \frac{f_{абс}}{L}, \quad (3)$$

Where Z_1 And Z_3 - elevation marks of the extreme points of the building structure in the considered section of the straight line.

To determine the magnitude (Fig. 5) of the deflection $f_{абс}$ and relative deflection $f_{отн}$ calculated using the formulas:

$$f_{абс} = \frac{2Z_2 - (Z_1 + Z_3)}{2}; \quad (4)$$

$$f_{отн} = \frac{f_{абс}}{L}, \quad (5)$$

Where Z_1 And Z_3 - elevation marks of the extreme points of the building structure in the considered section of the straight line.

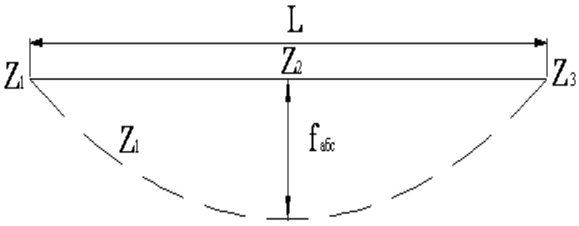


Figure 5-Geometric diagram of the deflection of floor beams.

The results obtained from the assessment of the technical condition of the structures using the above-described methodology were compared with the permissible values of SNiP - "Inspection and assessment of the technical condition of buildings and structures" Astana, 2015. The permissible value for the deflection of roof beams is 1/300 L, where L, m is the length of the beam. The permissible value of deviation of the columns of the enrichment plant structure is 15 mm, if the height is up to 4 meters.

5 CONCLUSIONS

Based on the research conducted by the authors:

1. A methodology for creating a support network for monitoring the deformation of bridges has been developed and geodetic monitoring of the transport interchange, as well as ground buildings, has been carried out.
2. The necessity of using satellite geodesy, electronic total stations and laser scanning methods for monitoring engineering structures is substantiated. For the installation of high-precision electronic and laser devices during geomonitoring of the earth's surface, the authors have developed a permanent forced centering point to ensure the speed and accuracy of centering, eliminating the use of tripods.
3. Methods for determining precipitation and displacement of structures are proposed. The research results were implemented during the implementation of a scientific project, as well as used in the educational process.
4. The novelty of the developed network and the design of the point are confirmed by the Certificates of the Republic of Kazakhstan for the product of science. The results obtained can be used to increase the level of industrial safety at other facilities and minimize the risks caused by the seismic activity in the area.
5.The creation of a monitoring network for high-precision observations of the condition of engineering structures using electronic and satellite GPS receivers has reduced the time spent on

determining coordinates in terms of one point being taken by 10-15 times and increased the accuracy of determining coordinates by at least 2 times.

Thus, the performed research has confirmed the effectiveness of an integrated approach to geodetic monitoring of the technical condition of engineering structures. The developed methodology can be recommended for use in similar engineering and geological conditions, and the results obtained can be used both in scientific and design and production practice.

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