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Analyzing geodetic leveling and subsidence of benchmarks: data and conclusions for Zhezkazgan and GEV-Lermontovo villages

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ABSTRACT
This article analyzes geodetic leveling data at sites in the villages of Zhezkazgan and GEV-Lermontovo for the period from 2014 to 2020 using correlation matrices, statistical tests, and box plots. Using the rock displacement data on benchmarks along selected profile lines, detailed analyses were conducted in two groups (Group "A" with the data from 2018 to 2020 and Group "B" with the in-depth study of subsidence levels since 2014). In group "A", correlation matrices were analyzed and statistically significant relationships were determined between the levels of subsidence of the benchmarks. Group "B" was aimed at studying changes in the level of subsidence along the three profile lines for different periods. Using box plots, the distribution and variability of subsidence levels were visualized, anomalies were identified and potential problem areas were identified. The results indicate significant subsidence on profile line 115 caused by mining activities in the area of the Lermontovo hydraulic fracturing site. These studies are valuable information for geodesists and geologists and can be used to manage urban development, infrastructure stability, and environmental protection in the region. The results obtained are of interest for further studies and can serve as the basis for the development of appropriate strategies and remedial measures.

Keywords: instrumental observations, geodetic monitoring, geodesy, leveling, profile lines

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Introduction

Monitoring, defined as the systematic observation of dynamic environmental conditions for control, analysis, and the prediction of changes, plays a pivotal role in assessing alterations in the natural world, often stemming from both natural phenomena, such as lithospheric plate movements and changes in weather conditions, and human activities, including soil reclamation and river channel modifications [1]. The progression of this field can be traced back to the 1990s when the widespread availability of Global Navigation Satellite Systems (GNSS) and the proliferation of GPS satellites enabled geodesists to meticulously track the Earth's crust movements with millimeter-level precision. This technological advancement shed light on the influence of seasonal shifts on tectonic movements and catalyzed investigations into surface load dynamics [2]. Nevertheless, satellite gravimetry exhibited certain limitations in the realm of geodesy. These restrictions stemmed from its temporal constraints, as despite the possibility of continuous online monitoring, the frequency of observations remained restricted to a few times a year. The expansion of observations through this method was further hindered by the intricate use of offshore platforms that combined geodetic positioning through GNSS and acoustic distance measurements [3]. As a response to these challenges, high-precision digital levels were developed for geodetic monitoring. Although their theoretical significance is well-established, their practical utility necessitates additional research and a thorough error analysis. Contemporary literature predominantly centers on the implementation of information technology in the analysis of data obtained from digital leveling methods, GNSS, and 3D sensors [4]. However, there remains a notable paucity in the discourse about the process of scrutinizing the acquired data through robust statistical metrics.

To address this identified gap in the literature, this study focuses on the analysis of instrumental observations in the Zhezkazgan and GEV-Lermontovsky districts since 1997. The data procured was categorized, evaluated for correlations, and trends, and juxtaposed against established benchmarks. The analytical framework is built upon the utilization of the R programming language. The study aspires to uncover insights into the connections between subsidence levels, discernible trends, and deviations from standard subsidence patterns across distinct lines. The credibility of the findings is underpinned by rigorous statistical modeling and the computation of p-values.

Experimental

A program for monitoring the subsidence of the earth's surface is being actively implemented at the Zhezkazgan field. The main measurement method used in this program is geodetic leveling used to analyze changes in surface level by accounting for differences in elevation.

Discussing the results

The measurement process is carried out along the network of 148 profile lines with a total length of 48 kilometers. The process of instrumental measurements includes the leveling of ground benchmarks located on profile lines No. 78, 79, 80, and 81. Benchmarks are placed above the areas where field development work has been carried out and are oriented by the main streets of the central and southern parts of the village. Instrumental observations cover profile lines No. 33 Bis 166, 77, 78, 76, 79, 80, 81, and 169, the total length of which is 4.39 kilometers. The integrated monitoring and measurement approach provides the necessary data to thoroughly assess the impact of resource extraction on the land surface and utilities [5].

The geodetic points established on the earth's surface and used for observations were usually placed near profile lines to ensure collecting the necessary data on the boundaries of the displacement area and key parameters of the process of deformation of the earth's surface. For observations, working and auxiliary geodetic benchmarks were used, including short-term driving ones. Such benchmarks were made of bar or drill steel and had a length of 1.5-2.0 meters and a diameter of 15 to 20 millimeters. When laying geodetic benchmarks in areas of the earth's surface where there was a risk of mechanical damage, the centers of the benchmarks were placed in special burials or holes [[6], [7]].

Observations of benchmarks at the geodetic station were carried out using a digital level. Such steps as Leica DNA03, lined invar slats, cast iron shoes and included the following:

1. Implementing planned and altitude reference reference points to the starting points and periodic monitoring of their immobility during observations.
2. Carrying out initial observations to determine the position of benchmarks at the observation station in the horizontal and vertical planes.
3. Measuring distances between benchmarks along profile lines.
4. Leveling all the benchmarks at the observation station.
5. Repeated observing the position of benchmarks at the observation station to determine the magnitude of their displacement.
6. Periodic surveys of cracks, failures and areas of collapse of the earth's surface [8].

Measurements in each period were performed in 2 series of observations. The information received was processed and the leveling of classes I and II was equalized by the requirements of the instructions [9]. Corrections are calculated with an accuracy of 1 mm. Their values are written with their signs above their corresponding excesses [10]. Collected over many years, multi-faceted data from different lines provides the completeness and reliability of the information needed to assess the impact of underground mining on the earth's surface and engineering infrastructure.

To identify the main relationships between the various geodetic profile lines, the lines were divided into two subgroups based on the available information. The first subgroup ("A") included profile lines with data from 2018 to 2020, while the second group ("B") focused on a more in-depth study of subsidence levels since the 2014s.

With the analysis of data available in group "A" for the period from 2018 to 2020, the priority task was to evaluate the correlation matrices. Correlation is a key concept in this statistical analysis that examines the relationship between variables in the context of their degree and direction [11]. The Pearson correlation coefficient, typically ranging from -1 to 1, indicates the strength and nature of the relationship between variables. A positive value means a positive correlation, indicating that as one variable increases, the other also tends to increase. Conversely, a negative value means a negative correlation, where increasing one variable corresponds to decreasing another. A correlation of 0 implies that there is no linear relationship between the variables [12]. This type of analysis was aimed at quantifying the strength and direction of connections between pairs of profile lines and was justified by the temporal proximity of the selected period, which made it possible to reduce the effect of external factors on the data, making the analysis more targeted and reliable [13].

In addition to identifying relationships, the key objective of this analysis was also to determine which pairs of profile lineages exhibited statistically significant associations. For this purpose, the generally accepted "p" value was used, which represents the probability of observing a strong correlation calculated under the condition that there was no actual relationship between the variables. When the p-value is below a predetermined significance level, which in scientific studies is set at 0.05, the correlation is considered statistically significant, rejecting the null hypothesis and proving that there is a 95% chance that the trend found is not due to chance [[14], [15]]. To apply this statistical test, the following hypotheses were used:

• *Null hypothesis* (H0 p<= 0.05): There is no relationship between the levels of subsidence of benchmarks from different lines.

• *Alternative hypothesis* (H1 p> 0.05): The relationship between the levels of subsidence of benchmarks from different lines is present and is not an accident based on statistical calculations.

Studying internal correlations in group "A" is of paramount importance, as it allows for identifying connections between the data that could be affected by common factors or events in a given period, which is valuable for making informed decisions and future forecasting [16].

Group "B" includes the data for three time intervals: 2014–2015, 2015–2018 and 2020–2024 The intervals were selected with the expectation that longer time periods could reveal broader and cyclical trends in the data [17]. These findings will be significant for long-term planning and identification of non-obvious patterns that might be missed in shorter intervals, such as in group "A".

In addition to separate analysis by groups, a general statistical assessment of all the profile lines was also carried out. For each data line study, both minimum and maximum values were determined according to all available information. This synthesis study, which is necessary to assess the spread of data and identify extreme values, can help establish control criteria and determine the limits of expected values in the future [18].

To demonstrate visually the distribution and variability of subsidence levels in each row, a box plot diagram method will be used. Box plots provide a condensed view of the distribution of data, showing the quartile mean and possible anomalies [19].

The overall line-by-line analysis process is presented in Table 1. All the analysis processes were carried out in the R programming language.

Table 1 – Research methodology

Characteristics of profile lines	Group A	Group B
Profile lines (Nos)	76. 77. 78. 169. 33. 166. 64. 195. 115. 60	79. 80. 81
Period	2018-2020	2014-2020
Analytical method	Correlation matrices and statistic test for significance	Identifying long-term regularities: cross analysis
General analysis for all the profile lines, building box plots		

Group A. In this study, we used the "corrplot" package in R to visualize the correlation matrix of the processed data [20]. The correlation matrix was calculated using rock displacement data on benchmarks along selected profile lines, organized using the order and eigenvalue method. The resulting correlation matrix shown in Figure 1a, provides a graphical representation of the relationships between variables: each cell in the matrix corresponds to the correlation coefficient between two variables, and the colors represent their intensities. And circular shapes are used to visually represent the strength and direction of these associations. This visualization technique allows quick and intuitive evaluating the relationships between variables, helping to identify potential patterns or relationships that may be of interest for further investigation. To the left of the cells is the color scale based on the Pearson correlation coefficient.

To highlight statistically significant relationships between variables, an additional correlation matrix plot was created (Figure 1b). This plot displays only statistically significant correlations based on the p value level <=0.05, and non-significant associations are represented by empty cells. Correlation coefficients are presented as numeric values in the upper triangle of the matrix, with black text and rotated 90 degrees to improve readability.

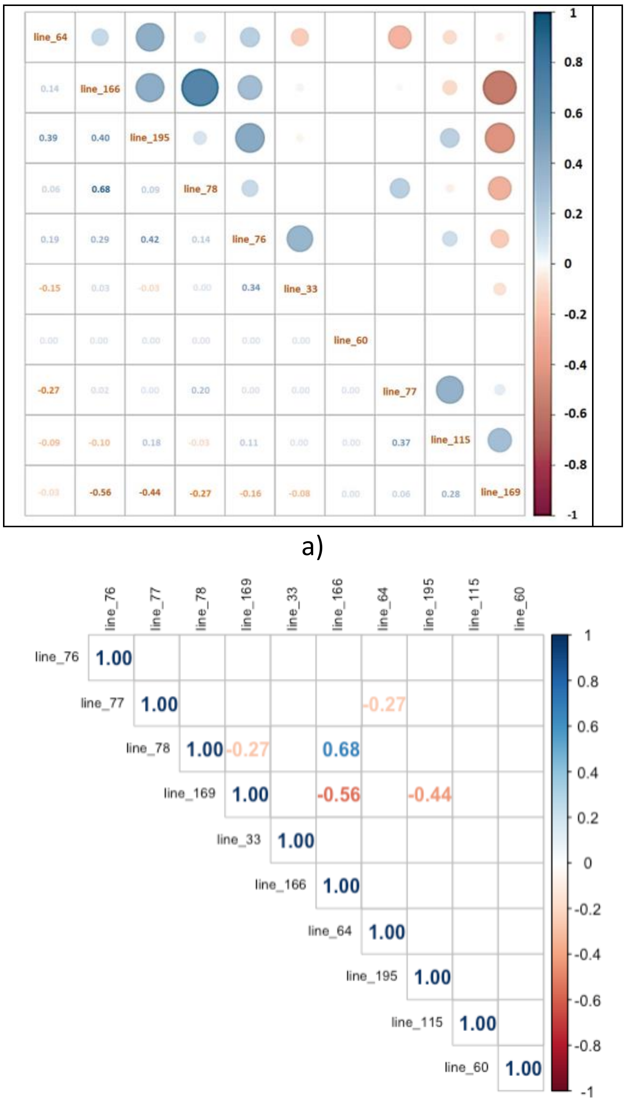


Figure 1 – Correlation matrices based on the analyzing profile lines in the group A: general values (a) and statistically significant correlations (b)

In total, of the 45 possible combinations, 28 showed any linear relationship between benchmark subsidence levels between 2018 and 2020, of which only five pairs showed statistically significant correlations sufficient to accept the alternative hypothesis. The presence of nonsignificant correlations highlights the selectivity of these five major pairs of variables in the context of our study.

Firstly, there was observed a moderate negative correlation (r=-0.27) between profile lines No. 74 and No. 64, which indicatess the inverse relationship. This correlation suggests that as the values in line No. 74 increase, the values in line #64 tend to decrease.

The same inverse relationship is reflected in the correlation between profile lines No. 79 and No. 169, where a similar negative correlation was revealed (r = -0.27). On the other hand, a strong positive correlation (r=0.68) was evident in the case of profile lines No.78 and No.166, confirming a strong linear relationship. In this scenario, as the values in line No. 78 increase, the values in line #166 show a corresponding increase. At the same time, the connection between line No. 169 and line No. 166 was characterized by a significant negative correlation (r= -0.56), which indicates a pronounced inverse relationship. In this case, the increase in values on line No. 169 is associated with a decrease in values on line No. 166.

Group B. The data represent changes in the level of subsidence of benchmarks along profile lines No. 79, 80, and 81 for three separate periods. To begin with, each line will be considered separately, then a comparative analysis will be carried out.

Overall, on line No. 79 (Figure 2), the data shows a noticeable downward trend in altitude at most control points over the three periods. The rate of decline varies, with some indicators showing greater changes than others. Data for the period 2014–2015. show an initial decrease in height. At the same time, benchmark No. 13 demonstrates the most significant subsidence at the level of -8.5 mm. Likewise, most benchmarks continue their negative trend during 2014–2018. At the same time, benchmark No. 13 demonstrates a noticeable decrease of -10.5 mm. During the period 2014–2020, the pattern continues, however, it is noteworthy that during this period there was a sudden subsidence of -13.1 mm at benchmark No. 32. In general, the most significant changes occur in the period 2014–2018, and in 2014–2020 this trend continues.

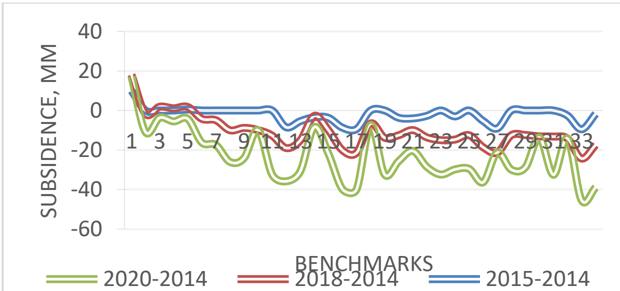


Figure 2 – Plot of benchmark subsidence on profile line No. 79

On line No. 80 (Figure 3) the data shows short-term fluctuations in benchmark levels. These fluctuations suggest local variations in decline or rise that are not part of a broader long-term trend.

Throughout the period from 2014 to 2020, the data shows a stable pattern or a slight increase and a very gradual stabilization. In the initial period (2014–2015), most indicators showed positive values, indicating a general trend of slight growth or stabilization. However, in the future, there was a noticeable variation on benchmark No. 10, where from 2014 to 2018 there was a significant decrease (-4.9 mm) in comparison with indicators No. 20 and No. 23, which showed positive levels of stabilization in the period from 2014 to 2020 Indicating the rise in the surrounding area. It is noteworthy to emphasize that signs about benchmarks Nos. 10, 22, and 24 exhibits more marked variations, suggesting the necessity for additional investigation into possible local issues. Conversely, such benchmarks as those Nos. 20 and 9 show consistent, albeit gradual, uplift, which may reflect regional geologic factors. In addition, Benchmarks Nos. 1, 2, and 7 show consistent patterns of uplift or slight subsidence over many years, which can provide valuable information to surveyors.

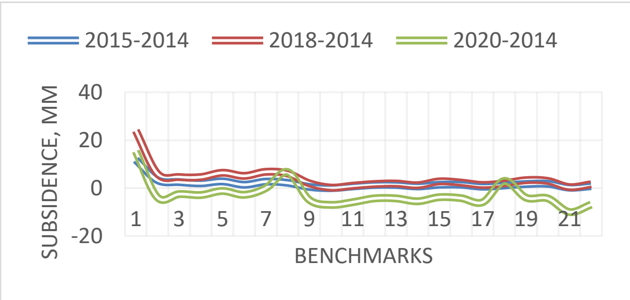


Figure 3 – Plots of benchmark subsidence on profile line No. 80

Examination of the line No. 81 data set (Figure 4) shows a consistent pattern of subsidence over three periods. At the same time, a significant decrease in height is recorded at control points. This subsidence pattern can have far-reaching consequences for the structural stability of buildings and infrastructure in the area. Benchmark No. 6 stands out as the most pronounced subsidence, decreasing by -6.8, -31.8, and -38.6 units over the corresponding time intervals. The other benchmarks also show a consistent decline in height, although not as steep as Benchmark No. 6.

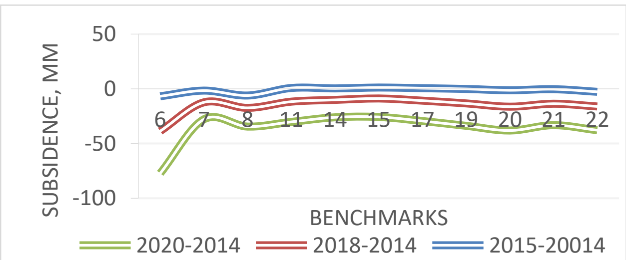
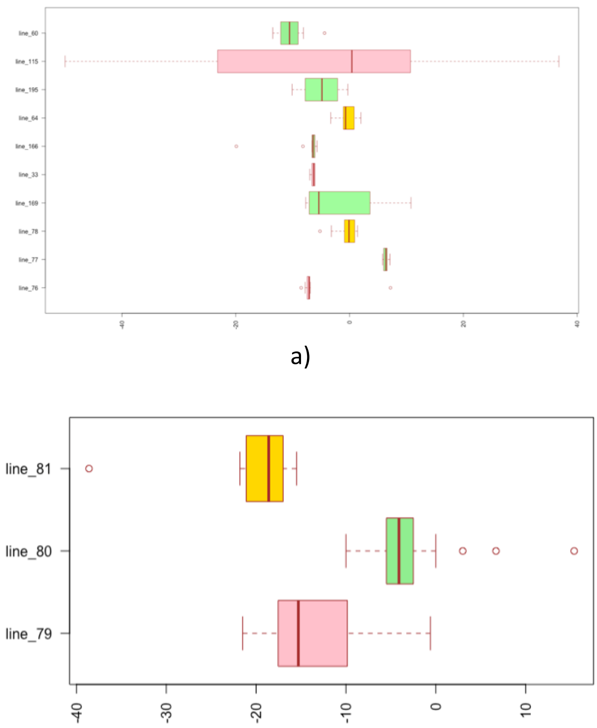


Figure 4 - Plots of benchmark subsidence on the profile line No. 81

In conclusion, the data set shows varied patterns of elevation change along lines 79, 80, and 81. While lines 79 and 81 consistently exhibit subsidence, line 80 exhibits variations in elevation with temporary stabilizations, likely due to local geologic conditions. These results highlight the need for in-depth geodetic and geological studies to identify the root causes of these changes and their potential implications for urban development, infrastructure stability, and environmental management in the affected regions.

General analysis. A box plot, also known as a box-and-whisker plot, is a graphical representation used to display the distribution and summary statistics of a numerical variable such as benchmark settlements. It consists of a rectangular “box” enclosing the interquartile range (IQR), which represents the middle 50% of the data. Within the box, a vertical line or "whisker" represents the median, which is the average value when sorting the data. The bottom and top edges of the box represent the first quartile (Q1) and third quartile (Q3), respectively that divide the data into four equal parts. The whiskers extend from the edges of the rectangle to the minimum and maximum values within a certain range, usually calculated as 1.5 times the IQR. Any data points outside this range are usually shown as individual points and are considered outliers. The boxplot provides a visual summary of the data's central tendency (median) scatter (IQR) and the presence of outliers. This is a valuable tool for comparing the distribution of a “linear” variable across different categories or periods, revealing potential patterns, skewness, and extreme values [21].

Among the identified results (Figure 5a, b), the boxplot for line No. 151 between 2018 and 2020 showed the greatest variability, as evidenced by a relatively wide interquartile range (IQR) with total variation starting from a maximum subsidence level of -50 mm. However, in comparison with other benchmark levels, no anomalies were identified in the case considered, while line No. 166 had the least variability during the same period. However, on a certain benchmark, an unusually low indicator was observed that did not fit into the maximum rate of change according to the average value along the profile line. The largest number of such emissions, indicating significant fluctuations in benchmarks within this category, was traced for line No. 80. All detected anomalies had a positive value. The changes indicated that certain benchmarks should be studied in more detail since they fall outside the typical range. The boxplot for profile line No. 33



a)

b)

Figure 5 – Box plot diagram for group A (a) and box plot diagram for group B (b)

showed the lowest variability with a relatively narrow IQR, suggesting that the rate of benchmark settlement remained more consistent and clustered around the median along the entire line.

In general, the geometric leveling paths laid at this site correspond to accuracy classes I and II. In the analysis carried out, from the results of instrumental observations carried out along the profile lines of the village Zhezkazgan and GEV-Lermontovo for the period from 2014 to 2020 there was revealed the greatest subsidence of the benchmarks along profile line No. 115, which ranges up to 50 mm. This is due to the fact that most of the territory of the village. The Lermontovo hydraulic fracturing site has been worked out, and the adjacent areas, in accordance with the deposit-by-deposit mining plans, are undergoing both primary and repeated development of reserves for different deposits, and there are also zones of multiple overlaps of mined-out areas.

Conclusion. As a result of the study based on the analysis of geometric leveling data in the village Zhezkazgan and GEV-Lermontovo for the period from 2014 to 2020, important conclusions were obtained significant for further geodetic, geological, and engineering research.

Firstly, a noticeable subsidence of the benchmarks was discovered in the areas under consideration, especially on some profile lines. This indicates the possible effect of underground geology and mining on the structure of the land in these areas. Such changes have significant implications for the safety of residents and infrastructure, so systematic monitoring and analysis is required to effectively control and manage risks.

Secondly, correlation matrices made it possible to identify both statistically significant and insignificant relationships between subsidence levels on different profile lines. These results highlight the complexity of the relationships between different variables and the need for a deep understanding of the factors influencing land surface changes.

Thirdly, box plots made it possible to visualize the variability of data over different time periods and along different profile lines. The identified anomalies indicate the need for further in-depth research to accurately determine the causes of such deviations and develop measures to prevent possible negative consequences.

Based on these findings, additional geological and geodetic studies are recommended, considering regional geological features and mining history. This approach will help to accurately identify the factors influencing benchmark settlement and plan effective measures to address potential risks to the structural stability and safety of site occupants. Only such efforts will ensure sustainable development and guarantee the long-term safety of infrastructure.

Final results

1. The in-depth analysis of instrumental observations along profile lines in the Zhezkazgan and GEV-Lermontov areas since 1997 made it possible to identify significant fluctuations in the levels of benchmarks subsidence on various profile lines within the period under review.

2. A significant part of the village area in the Lermontovo hydraulic fracturing site is subject to overworking, and there are also zones of multiple overlaps of mined-out areas, which causes significant fluctuations and anomalies in the levels of benchmark subsidence, exceeding the maximum rate of change.

3. Box plots constructed for Group A and Group B showed varying levels of variability and shifts in benchmarks depending on the profile lines,

indicating the need for additional research and monitoring in these areas.

4. The analysis of benchmark subsidence using digital levels and correlation matrices made it possible to identify statistically significant patterns and trends, which confirms the need for constant monitoring and control of the state of the earth's surface in these areas.

5. The development of observation programs at stations and the analysis of error sources are the key points to ensuring the accuracy and reliability of the data when carrying out geodetic measurements and leveling on the specified profile lines.

These findings highlight the need for a systematic and comprehensive approach to monitoring and analyzing benchmark subsidence, especially under conditions of increased tectonic activity and geological changes in the studied areas.

Conflicts of interest. On behalf of all the authors, the corresponding author declares that there is no conflict of interest.

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Геодезиялық нивелирлеу және реперлердің шөгуін талдау: Жезқазған және ГБК-Лермонтово кенттері бойынша мәліметтер мен қорытындылар

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ТҮЙІНДЕМЕ
Мақалада 2014-2020 жылдарға арналған Жезқазған және ГБК-Лермонтово кенттерінің учаскелерінің геометриялық орналасуы туралы мәліметтер корреляциялық матрицалар, статистикалық сынақтар және қорап диаграммасы арқылы талданған. Таңдалған профильді сызықтар бойынша реперлерде тау жыныстарының жылжуы туралы деректерді пайдалана отырып, егжей-тегжейлі талдаулар екі топта жүргізілді («А» тобы 2018 жылдан 2020 жылға дейінгі деректер және 2014 жылдан бастап шөгу деңгейі терең зерттелген «Б» тобы). «А» тобында корреляциялық матрицалар талданды және эталондық шөгу деңгейлері арасында статистикалық маңызды байланыстар анықталды. «Б» тобы әртүрлі кезеңдердегі үш профильдік сызық бойынша реперлердің шөгу деңгейіндегі өзгерістерді зерттеуге бағытталған. Қорап диаграммаларын пайдалана отырып, шөгу деңгейлерінің таралуы мен өзгермелілігі визуалды түрде көрсетілді, ауытқулар және ықтимал проблемалық аймақтар анықталды. Нәтижеде Лермонтово гидравликалық жару аймағында тау-кен жұмыстарын жүргізу нәтижесінде № 115 профиль сызығы бойынша айтарлықтай шөгу байқалады. Зерттеу деректері маркшейдерлер мен геологтарға құнды ақпарат береді және сонымен қатар аймақтағы қаланы дамыту, инфрақұрылымның тұрақтылығы мен қоршаған ортаны қорғауды басқару үшін пайдаланылуы мүмкін. Алынған нәтижелер кейінгі зерттеулер үшін қызығушылық тудырады және теріс салдарларды жою бойынша тиісті стратегиялар мен шараларды әзірлеу үшін негіз бола алады.

Түйін сөздер: аспаптық бақылаулар, геодезиялық мониторинг, геодезия, нивелирлеу, профильді сызықтар

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Анализ геодезического нивелирования и оседания реперов: данные и выводы для Жезказганского и ГРП-Лермонтово поселков

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АННОТАЦИЯ
В данной статье проведен анализ данных геометрического нивелирования на объектах в пос. Жезказган и ГРП-Лермонтово за период с 2014 по 2020 гг. с использованием корреляционных матриц, статистических тестов и коробчатых диаграмм. Используя данные о смещении пород на реперах по выбранным профильным линиям, были проведены детальные анализы в двух группах (группа "А" с данными с 2018 по 2020 годы и группа "Б" с углубленным изучением уровня оседаний с 2014 года). В группе "А" был проведен анализ корреляционных матриц и определение статистически значимых связей между уровнями оседаний реперов. Группа "Б" была направлена на изучение изменений уровня оседаний реперов вдоль трех профильных линий за различные периоды. С использованием коробчатых диаграмм было визуализировано распределение и изменчивость уровня оседаний, выявлены аномалии и установлены потенциальные проблемные участки. Результаты указывают на значительные оседания, на профильной линии №115, вызванные горными работами в районе ГРП-Лермонтово. Данные изучения являются ценной информацией для специалистов-геодезистов и геологов, а также могут быть использованы для управления городским развитием, стабильностью инфраструктуры и охраной окружающей среды в данном регионе. Полученные результаты представляют интерес для проведения дальнейших исследований и могут послужить основой для разработки соответствующих стратегий и мер по устранению негативных последствий.

Ключевые слова: инструментальные наблюдения, геодезический мониторинг, геодезия, нивелирование, профильные линии

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