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RESEARCH ARTICLE

IMPROVING METHODS OF GEODETIC MONITORING OF HYDRAULIC STRUCTURES USING THE EXAMPLE OF KAPSHAGAY HPP

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Abstract. *This article provides recommendations for enhancing geodetic monitoring methods for deformation processes at the Kapshagay Hydroelectric Power Station (HPP), a key component of Kazakhstan's energy infrastructure. In this context, improved methodology for geodetic surveys incorporating modern measurement instruments is proposed. The article explores various methods and approaches to geodetic monitoring of hydraulic structures at the HPP, with a particular focus on leveling and cross-section measurements. These techniques are essential for analyzing sedimentation and displacement, ensuring high accuracy in determining changes in plan-height coordinates. The paper details geodetic network utilized, which includes fundamental rock benchmarks, soil marks, and forced centering points, along with the measurement techniques applied. Additionally, key aspects of instrumental surveys - such as ultrasonic testing and ground-penetrating radar - are examined, as these technologies aid in detecting hidden defects and enhancing structural safety. The study confirms that leveling and cross-sectional measurements enable reliable monitoring of both vertical and horizontal deformations. Furthermore, integration of fundamental rock benchmarks, soil marks, and forced centering points ensures a high level of measurement accuracy while minimizing errors. The novelty of the proposed methods and means of monitoring are confirmed by Patents and Author's Certificates of the Republic of Kazakhstan.*

Keywords: *Kapshagay HPP, geodetic monitoring, hydraulic structures, leveling, deformation network, ultrasonic testing, structural safety.*

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ҒЫЛЫМИ МАҚАЛА

ҚАПШАҒАЙ СУ ЭЛЕКТР СТАНЦИЯСЫНЫҢ МЫСАЛЫНДА ГИДРОТЕХНИКАЛЫҚ ҚҰРЫЛЫСТАРДЫ ГЕОДЕЗИЯЛЫҚ МОНИТОРИНГТЕУДІҢ ӘДІСТЕРІН ЖЕТІЛДІРУ

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Аңдатпа. *Мақалада Қашағай СЭС деформациялық процестерінің геодезиялық мониторингі әдістерін жетілдіру бойынша ұсыныстар келтірілген. Қапшағай су электр станциясы (СЭС) Қазақстанның энергетикалық инфрақұрылымында маңызды нысан болып табылады. Осыған байланысты геодезиялық жұмыстарды жүргізудің және оларда заманауи өлшеу құралдарын пайдаланудың жетілдірілген әдістемесі ұсынылды. Мақалада су электр станцияларының гидротехникалық құрылыстарының геодезиялық мониторингінің әдістері мен тәсілдері қарастырылады. План-биіктік координаталарындағы өзгерістерді анықтауда жоғары дәлдікті қамтамасыз ететін құрылымның шөгуі мен орнының ауытқуларын талдау үшін нивелирлеу және жармалық өлшеу әдістеріне ерекше назар аударылады. Пайдаланылатын геодезиялық желінің сипаттамасы, оның ішінде іргелі тау жыныстарының эталондары, жер белгілері және мәжбүрлі орталықтандыру нүктелері, сондай-ақ оларды өлшеу әдістері келтірілген. Жасырын ақауларды анықтау және құрылымдардың қауіпсіздігін қамтамасыз ету үшін қолданылатын ультрадыбыстық сынау және жерге енетін радар сияқты аспаптық тексерудің негізгі аспектілері қарастырылады. Нивелирлік және көлденең қималарды өлшеу әдістерін қолдану деформация желісінің тік және көлденең параметрлерінің өзгеруін сенімді бақылауға мүмкіндік беретіні анықталды. Ал іргелі тау жыныстарының эталондарын, топырақ белгілерін және мәжбүрлі орталықтандыру нүктелерін пайдалану өлшеу дәлдігінің жоғары деңгейін және қателерді азайтуды қамтамасыз етеді. Қалыптасқан геодезиялық желі тұрақты бақылаудың сенімді негізін қамтамасыз етеді, ал II дәрежелі дәлдіктегі геометриялық нивелирлеуді қолдану көлденең және тік координаталардағы тіпті ең аз ауытқуларды жедел анықтауға мүмкіндік береді. Ұсынылған мониоирингтің әдістері мен жабдықтарының жаңалығы ҚР патенттері және авторлық құқық куәлігімен расталған.*

Түйін сөздер: *Қапшағай ГЭС, геодезиялық мониторинг, гидротехникалық құрылымдар, нивелирлеу, деформацилық торап, ультрадыбыстық бақылау, құрылымдардың қауіпсіздігі.*

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НАУЧНАЯ СТАТЬЯ

СОВЕРШЕНСТВОВАНИЕ МЕТОДОВ ГЕОДЕЗИЧЕСКОГО МОНИТОРИНГА ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ НА ПРИМЕРЕ КАПШАГАЙСКОЙ ГЭС

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Аннотация. *В статье приведены рекомендации по совершенствованию методов геодезического мониторинга дефоромационных процессов Кашагайской ГЭС. Капшагайская гидроэлектростанция (ГЭС) является важным объектом энергетической инфраструктуры Казахстана. В связи с этим предложена совершенствованная методика проведения геодезических работ и использования в них современных средств измерений. Рассмотрены методы и подходы к геодезическому мониторингу гидротехнических сооружений ГЭС. Особое внимание уделено методам нивелирования и створных измерений для анализа осадков и смещений, которые обеспечивают высокую точность определения изменений планово-высотных координат. Приведены описания используемой геодезической сети, включающей фундаментальные скальные реперы, грунтовые марки и пункты принудительного центрирования, а также методов их измерения. Рассмотрены ключевые аспекты инструментального обследования, такие как ультразвуковой контроль и георадиолокация, которые применяются для выявления скрытых дефектов и обеспечения безопасности сооружений. Установлено, что Использование методов нивелирования и створных измерений позволяет надежно контролировать изменения как вертикальных, так и горизонтальных параметров деформационной сети. А применение фундаментальных скальных реперов, грунтовых марок и пунктов принудительного центрирования обеспечивает высокий уровень точности измерений и минимизацию погрешностей. Сложившаяся геодезическая сеть предоставляет надежную основу для регулярного мониторинга, а применение геометрического нивелирования II класса точности позволяет оперативно выявлять даже минимальные отклонения в планово-высотных координатах. Новизна предложенных методов и средств мониторинга подтверждены Патентами и авторскими Свидетельствами РК.*

Ключевые слова*:* *Капшагайская ГЭС, геодезический мониторинг, гидротехнические сооружения, нивелирование, деформационная сеть, ультразвуковой контроль, безопасность сооружений.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

The Kapchagay Hydroelectric Power Plant (HPP) plays a crucial role in Kazakhstan's energy infrastructure. Its reliable operation depends on the condition of its hydraulic structures, making regular monitoring essential for ensuring both safety and operational efficiency.

Hydropower plays a key role in Kazakhstan's strategy to diversify its energy sector. In this context, the Kapchagay Hydroelectric Power Station, named after Sh. Chokin, holds particular significance as the only hydroelectric power plant on the Ili River. Construction of the main structures began in 1966, and the station was fully completed by 1980. The Kapchagay HPP was built to supply the growing city of Almaty and its surrounding satellite towns with affordable electricity (**Figure 1**).

Figure 1 - General view of the Kapchagay hydroelectric power station

Today, the Kapchagay Hydroelectric Power Station remains a key factor in the development of the city of Konayev, supporting the growth of its communal, educational, medical, and cultural infrastructure. The city's rapid expansion, marked by changes in urban planning and the emergence of large new structures, alongside the safe operation of strategic engineering facilities like the Kapchagay HPP, is ensured through geodetic monitoring.

2 LITERATURE REVIEW

Geodetic monitoring of engineering structures, including hydraulic facilities, involves a wide range of measurement methods and tools. GPS technologies, electronic and laser instruments, ground-penetrating radar devices, and various sensors are effectively used to track horizontal displacements (**Genike et al., 2010; Nikonov et al., 2013, Hiller et al., 2015**). Construction of hydroelectric power plants, like any other large structures, requires the establishment of reference geodetic network. This network must be created within a unified coordinate system and ensure high positioning accuracy. Reference points of geodetic network should be strategically placed, considering configuration of observed structures. Crucial aspect of this process is the use of modern instruments and diverse control methods to enhance monitoring accuracy (**Skripnikov, 2010; Salnikov et al., 2018; Nurpeissova et al., 2020**).

According to the rules approved by the order of the Ministry of Agriculture of the Republic of Kazakhstan dated March 31, 2015 №. 19-4/286, hydraulic structures that have been in operation for more than 25 years are subject to mandatory annual multifactorial inspection. These activities are aimed at identifying potential risks and maintaining safe operation of facilities. The main areas of such inspection include:

1. Detailed assessment is conducted on structural parameters that may affect stability and strength. Key focus areas include changes in loads and external impacts, the occurrence of deformations and displacements, as well as the deterioration of surface layers due to corrosion or cavitation.
2. Evaluation of operability and reliability of mechanical equipment, including valves, gratings, embedded elements, and fittings. Inspection process also includes quality control of welded joints and metal structures of lifting mechanisms.
3. Assessing technical condition of underwater structural components through underwater video filming, which helps identify damage and evaluate the integrity of structural elements.
4. Performing emergency surveys following extreme natural events or accident.

Analysis is also conducted to evaluate adequacy of measures taken by the owner to prevent emergency situations. This enables timely adjustments to facility management strategy and helps prevent the escalation of critical situation.

Hydraulic structures (HS) of the Kapchagay HPP comprise numerous components, the condition and functionality of which are crucial to the overall safety and reliability of station. Since the completion of the HPP in 1980, passage of time has significantly affected condition of these structures (**Order of the Minister of Agriculture of the Republic of Kazakhstan; Kuznetsov, 2007**).

The primary causes of defects and deterioration in structural elements include:

- Physical wear and tear of materials and aging of structures;
- Seasonal temperature fluctuations, which further impact materials;
- Seasonal variations in water levels in the reservoir, leading to changes in load;
- Landslides and avalanches in the reservoir area, resulting from changes in soil strength characteristics;
- Erosion of slope linings and fastenings due to wave action;
- Damage to dam and embankment slopes caused by precipitation;
- Ice load effects on the upper slopes of the dam;
- Damage to concrete structures due to leaching, filtration, and other factors;
- Deterioration of metal and concrete elements due to cavitation and corrosion;

Non-compliance with regulations for the maintenance and operation of hydraulic structures (**Nurpeissova et al., 2023**).

In accordance with regulatory documents and procedures, surveys are conducted at specified intervals to analyze and identify deviations of the structure from its «normal» state. Survey process is carried out in multiple stages, including both visual and instrumental inspections.

Visual inspections help identify external signs of processes that lead to changes in the condition of the objects being studied, which can only be partially monitored through instrumental observations. Due to the precision of visual control, visual inspections remain the most efficient and effective method for assessing the condition of these objects (**Salih et al., 2016; Sholomitsky et al., 2023**).

Visual inspections focus on identifying external signs that indicate changes in the condition of structures and their components. The following activities are performed during these inspections:

- Inspection of the earth dam: condition of the soil is evaluated to detect subsidence, heaving, sinkholes, landslides, gullies, and the effects of rain and meltwater. Additionally, the nature of the vegetation, signs of seepage such as spots, springs, and ice on the downstream slope, as well as the presence of longitudinal and transverse cracks, are also considered.
- Checking control and measuring equipment: inspection of technical devices used to monitor condition of the dam is carried out.
- Examination of the junction zone between the dam, foundation, and side abutments: signs of subsidence, gullies, cracks, seepage, and soil erosion are identified.
- Inspection of adjacent areas from downstream side: particular attention is given to the side abutments to detect landslides, areas of collapse, bulging, erosion, weathering of slopes,

waterlogging, the release of muddy seepage water, and other defects that may indicate structural instability.

Instrumental examination methods:

- *Ultrasonic testing* is used to measure the thickness of metal walls of structures such as embedded parts, gratings, water inlets and guide structures. Special ultrasonic devices are used that provide high measurement accuracy. For example, ultrasonic thickness gauges of the «TUZ-5» type allow for detailed analysis even in difficult operating conditions.
- *Methods of georadar and geoacoustic sounding* are based on principles of electromagnetic and acoustic tomography. They are used to study underwater and underground parts of structures, which allows for detection of hidden cavities, cracks and destruction. Instruments such as «OKO-2» provide ability to construct detailed models of internal state of soils and structures.
- *Stress and deformation monitoring systems*. Control and measuring devices are used to continuously monitor changes in the design of dams, locks and other parts of the hydraulic structures. These devices allow critical deviations in parameters to be identified in real time (**Penman, 1999; Arvindan et al.; Operational Documentation of the Kapshagai HPP**).

3 MATERIALS AND METHODS

Safe operation of such strategic engineering structures is ensured through comprehensive monitoring, utilizing GPS technologies, electronic tacheometers, ground scanning, and automated observation methods, all while adhering to strict operational conditions.

4 RESULTS AND DISCUSSION

Geodetic deformation monitoring is one of the key instrumental methods used to determine settlements and shifts in hydraulic structures. This technique allows for high-precision recording of positional changes at individual points, revealing the dynamics of deformation caused by both external and internal factors (**Author's certificate for a scientific work of the Republic of Kazakhstan №. 39036**).

At the Kapchagay Hydroelectric Power Station, geodetic monitoring is conducted on the channel and ravine dam, as well as on the station site with the 220 kV outdoor switchgear. Monitoring work on these sites includes leveling of ground and surface points to measure settlements, and cross-section measurements using a tacheometer to determine structural displacement.

Result of these works is determination of changes in planimetric and vertical coordinates of deformation network, which consists of both deep and surface marks. Previously established geodetic network, including forced centering points (FCP) (**Figure 2a**), points of fundamental rock benchmarks (**Figures 2b** and **2c**), and soil marks (**Figures 2d** and **2e**), serves as a control leveling network for determining vertical deformations. Supporting vertical benchmarks are installed on the rock base, with the center accessible for reference. In contrast, the observed marks are placed within the dam body and are protected by an external pipe. These marks are positioned at a depth of 0.5 meters, making them convenient for staff installation. Measurements are carried out using the geometric leveling method with class II accuracy, between the supporting fundamental benchmarks and the control soil and surface marks. Horizontal displacement is determined through alignment measurements from the base line points.

Figure 2 - *a* - FCP, *b and c* - reference leveling network points; *d* and *e- soil marks*

To monitor the deformation of the Kapchagay Hydroelectric Power Station, a new geodetic point of forced centering (PPC) was proposed as a permanent reference, in accordance with regulatory standards (**Patent of the Republic of Kazakhstan № 35798**). Monitoring was conducted using a GPS system, with results cross-verified by a Leica Geosystems TCR1201 electronic tachometer. The geodetic base coordinates were determined in the local system, while altitude coordinates were referenced to the Baltic system. Benchmark elevations were established using the alignment method. During alignment, the planned positions of control ground and surface benchmarks were monitored. The alignment diagram is shown in **Figure 3**, and the subsidence graph along alignment line I-I is presented in **Figure 4**.

Figure 3 - Alignment lines to control horizontal displacement (marked in red).

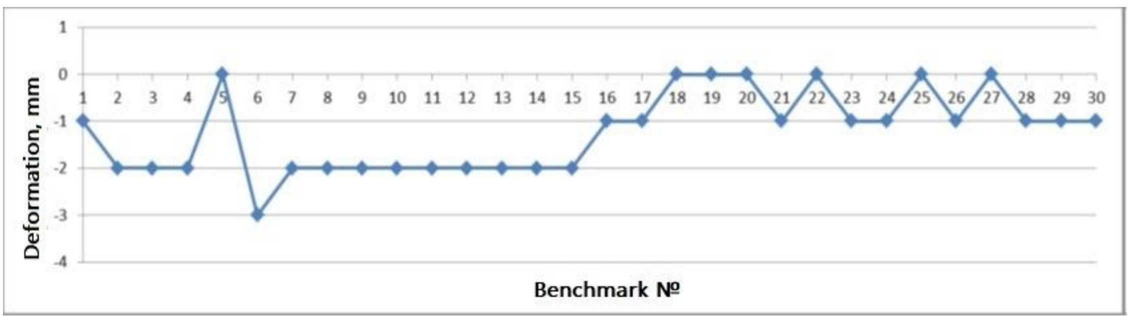

Figure 4 - Graph of benchmark subsidence along the I-I alignment line (observation date /25/042024)

Use of leveling and cross-sectional measurements allows for reliable monitoring of changes in both vertical and horizontal parameters of the deformation network (**Nurpeisova et al., 2021; Myngzhasrov et al., 2024**).

5 CONCLUSIONS

Geodetic monitoring is essential for ensuring the safety and efficiency of engineering structures. It enables real-time tracking of deformations and movements, allowing for the early detection of potential risks and structural threats. This proactive approach helps prevent emergencies by facilitating timely intervention and maintenance.

Integration of fundamental rock benchmarks, soil marks, and forced centering points ensures high measurement accuracy while minimizing errors. Established geodetic network serves as a reliable foundation for continuous monitoring, while geometric leveling of the II accuracy class enables the prompt detection of even minor deviations in plan-height coordinates.

As a result of the research, geodetic reference point for forced centering was developed and implemented in practice, enhancing both the accuracy and efficiency of observations.

Practical significance of this work lies in its application in master's and doctoral dissertations, as well as in the educational process at the Kazakh National Research Technical University named after K.I. Satpayev and the International Educational Corporation (IEC). Additionally, results can contribute to improving industrial safety at other construction sites.

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