Inclinometer-Based Long-Term Monitoring of the Headframe of Salt Mine Shaft

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Abstract. The paper presents a block diagram of an automated inclinometer -based system for monitoring the inclination of a high-rise metal structure of the shaft headframe. The stress-strain state of this structure is defined by the loads associated with the operation of shaft skip and the impact of the environmental factors on the structure. The data obtained by 6 inclinometers located at different height were used to determine the inclination of the headframe and distortion of its shape. Analysis of long-term observation data revealed the existence of deformation processes having different time scales (long-term, seasonal and daily). A correlation between changes in the tilt angle of the structure and ambient temperature was established. Long-term monitoring of tilt angle showed that the displacements of the structure were within the permissible limiting values. The developed monitoring system is of great theoretical importance for understanding the deformation processes arising during the operation of such structures.

1. Introduction

Control of the spatial position of various engineering and building structures is along-sanding issue. Precise positioning of structures in space is of special concern to engineers when creating geotechnical structures, such as dams, roads, underground tunnels, wells. The problem becomes vital in the construction of complex high-rise buildings and industrial structures. Inclinometric control systems are designed to determine the angular displacement of structure elements. Inclinometers, tiltmeters of various designs are based on the principle of recording the deviation of a horizontal or vertical surface from the direction of the gravity vector. They can be used both in a single-use mode and in continuous monitoring mode. They are often used as a part of automated systems for integrated monitoring of the stress-strain state of the monitored structures.

There are many examples of equipping various engineering structures with automated deformation monitoring systems, which include tilt control devices. Such systems are installed on high-rise buildings [1-4]. Thus, the monitoring system of high-rise Canton Tower [3] contains an inclinometric control system comprising 12 tiltmeters located at different height. Historical structures are equipped with tilt control systems to assess their safety and longevity [5-8]. It is especially important to use tilt monitoring systems in conditions of instability of soil foundation, or in the case of high and non-uniform external loads associated with different natural factors, weather events or the operation of technological equipment. Works [9-11] describe the application of the systems for controlling the inclination of the shaft head when extracting ore from the mine.

The concept of the inclinometric control system is based on the mechanical condition of the structure, specific working conditions and specific tasks, which are set when organizing structure deformation monitoring. In modern structural health monitoring systems, the data of inclinometric measurements can be used both for independent analysis of the structural damage and for comparison with data obtained with the aid of other recording systems. This data is very important for verification of the mathematical model used to describe the deformation processes in the structure.

This paper describes the structure of inclinometer system for online monitoring of the over-mine skip shaft construction. The results of measurements, which were obtained with inclinometers distributed
over the elements of the structure, are analyzed to determine the factors determining the tilt-angle distribution throughout the height of the structure and its changes at different time scales.

2. The system of deformation monitoring of the over- mine structure of skip salt shaft
The purpose of research carried out by our team was to organize monitoring of the stress-strain state of the above-ground shaft structure, which is a metal prefabricated construction 65 m high. The load-bearing elements are steel pillars, connected by vertical and horizontal coupling beams into a frame system. One part of the structure supporting elements rests on the pile foundation, and the other part - on the reinforced concrete shaft head. The mineshaft extends to a depth of 800 m. The installation of the deformation monitoring system was carried out in parallel with the construction of the headframe, which allowed us to obtain experimental data on the mechanical condition of the structure at the very beginning of its life cycle.

The shaft has a diameter of 8 m and a depth of 800 m. A special device for lifting rock salt to the surface, which is called a skip, moves inside the shaft. The movement of the skip is provided by the mine hoist, the sheave wheels of which are located in the upper part of the shafthead frame. The stress-strain state of the shafthead is determined by the weight of the framehead itself and the skip, the dynamic action of the hoisting system, the interaction of the shaft head construction with the reinforce concrete head of the shaft and the ground, as well as environmental factors (wind pressure, temperature effect, ice load etc.). The need to control the vertical position of the structure is dictated by the integrity and durability considerations as well as the possibility of unobstructed movement of the skip along the entire length of the shaft. With account of all these requirements, the maximum permissible displacement of the upper part of the headframe relative to its initial position is set equal to 116 mm.

Our research team has developed and constructed an original system for automated monitoring the stress-strain state of this structure. It contains 3 independent measuring units: for monitoring the vertical and axial strains in the base of supporting pillars; for vibration control of the headframe and for controlling the vertical deflection of the structure. The acquisition of monitoring data is carried out online, data storage and processing, as well as the management of the monitoring system is performed remotely.

3. System for monitoring headframe inclination
The tilt control system contains 6 inclinometers uniformly distributed along the height of the structure. Five sensors were located on one supporting pillar and one additional sensor was fixed at the top of the adjacent pillar (figure 1). Such arrangement of sensors allowed us to detect the distortion of space shape of the supporting pillars. The information recorded by inclinometers was transferred to the primary data collection unit and then delivered to the server for processing and subsequent storage.

By use of tiltmeters, rigidly attached to the supporting pillars, we can measure small angles of inclination of the object in two mutually perpendicular XOZ and YOZ planes. The inclinometer unit includes sensors with the following characteristics: angle measurement range is +/- 3600 arc. sec, measurement error is 0.5 arc. sec. Tilt measurement resolution can be set arbitrarily, and in accordance with the objective of our research was taken equal to 10 minutes.

In fig. 1, which reproduces the page of monitoring system website, the values of tilt angles in angular seconds corresponding to a certain moment of observations are shown next to the number of the sensor.

The data collected by the inclinometer system, were used to calculate the distribution of displacements in the X and Y directions along the vertical coordinate and construct the spatial shape of the pillar axis at the time of observation. The information was accumulated in the database of the monitoring system, which made it possible to analyze the changes in the spatial position of the structure for any time period.

4. Results of inclination measurements
Figure 2 shows the data obtained after primary processing of tilt measurements. The displacements in the direction of the X and Y axes are determined as a function of the vertical coordinate in two mutually perpendicular planes. These functions are constructed with the use of quadratic splines, which ensure the continuity of the displacement function and its first derivative. For the observation period of 9 months, the initially straight supporting pillar became curved. In figure 2, the dark lines show the projections of the supporting pillar onto the XOZ and YOZ planes. The corresponding values of the
displacement in the horizontal plane are shown near the sensor icons. For clarity, horizontal displacements are shown on a larger scale. The results of monitoring show, that the current horizontal displacement of the upper part of the supporting pillar is 12 mm and does not exceed the limit values determined by the technical conditions of the structure. The lower part of the figure shows the current position of the top point of the headframe. The colored circle designates the permissible horizontal displacements, and the red point corresponds to the position of the top of supporting pillar.

Figure 1. Layout of inclinometers on the headframe.

Figure 2. The shape of the deformed axis of the supporting pillar and deviation of the top of the structure relative to its initial position.
During the operation of the automated monitoring system, a large data set, reflecting time variation of the tilt angles at the reference points of the supporting pillar was generated. Figure 3 shows the data of monitoring at three different points on the pillar of the headframe. Sensors 1, 3 and 5 are installed at the height of 10, 32 and 58 m, respectively. The left column of graphs in the figure shows the evolution of the tilt angles in the XOZ plane, and the right column shows similar dependences in the YOZ plane. Red lines show the current values of the tilt angles, and green lines show the data averaged over the daily period.

Analysis of these data shows that over a 9-month observation period, the largest changes in the tilt angles were recorded at the base of the pillar (sensor 1) and at the top of the structure (sensors 5 and 6). These values are 105, 120 and 180 arc seconds, respectively.

Analysis of the obtained time series made it possible to identify some patterns of structural deformation. Observed changes in the tilt angles show different trends at different time scales. Figure 4 shows the data received from sensor 5 located at the height of 58 m. They are compared with the temperature readings, which are also recorded by one of the sensors of the monitoring system.

Long-term observation data revealed a tendency for monotonic increase in the inclination of the structure in the XOZ and YOZ planes (figure 4, top row). At the current moment, the values of the tilt angles are +89 and –141 arc seconds, respectively. In the graphs corresponding to a 1-month observation period (middle row), you can clearly see fluctuations in the tilt values consistent with daily changes in the ambient temperature. The graphs for a 2-day observation period (bottom row) reflect not only daily tilt fluctuations, but also fluctuations with higher frequency. It is possible that these fluctuations can be compared with the operating modes of the mine hoisting system.

The detected relationship between the tiltmeter readings and the ambient temperature is confirmed by a statistical analysis of the accumulated data. Figure 5 shows the graphs that compare the values of the tilt angle and ambient temperature for the entire observation period. These data correspond to the sensors located at the base, in the middle and at the top (sensors 1, 4 and 5) of the structure. Based on these data, we calculated the values of the correlation coefficient $R^2$, which are shown in the graphs.
From the obtained data it follows that the most significant correlation between the angles of inclination and temperature is observed in the lower part of the structure adjacent to the head of the mineshaft. This effect can be associated with the processes caused by the interaction of the headframe with the concrete head of the mine and the surrounding soil. The supporting pillars of the structure, resting on the reinforced concrete head of the shaft, experience the influence of the underground part of the shaft, which is in significantly different temperature conditions. The above effect is consistent with the data obtained by another independent unit of our monitoring system - the hydraulic leveling system. Differential settlement of supporting pillars recorded by this system correlates well with a change in ambient temperature.

Figure 4. Changes in the tilt angle of the structure for different observation intervals (Sensor 5, height of 58 m).

Figure 5. Tilt angle as a function of ambient temperature (9-month observation data).
5. Conclusions
A system has been developed for monitoring the tilt angles of the headframe of the skip shaft, which provides proper control over the displacement of the sheave wheels of mine hoisting located in the upper part of the headframe.

On-line monitoring of the tilt angles for 9-month period shows that the displacement of the top of the headframe does not exceed the permissible value.

The inclinometric measurements provide the necessary data for verifying the mathematical model of deformation processes occurred in the headframe. Using the verified model we can estimate the development of the deformation state of the structure and prevent the occurrence of its critical state.

The developed system of online monitoring the tilt angles of the mine structure revealed the existence of deformation processes at different time scales (long-term, seasonal, daily).

The revealed correlation between the changes in the tilt angle and temperature led us to the conclusion that the ambient temperature is one of the main factors affecting the inclination of the structure.

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References
[1] Su J Z, Xia Y, Chen L et al 2013 Long-term structural performance monitoring system for the Shanghai Tower J Civil Struct Health Monit 3 49
[2] Yigit C O, Li X J, Inal C, Ge L and Yetkin M 2010 Preliminary evaluation of precise inclination sensor and GPS for monitoring full-scale dynamic response of a tall reinforced concrete building J Appl Geodesy 4 103
[3] Xia Y, Zhang P, Ni Y and Zhu H 2014 Deformation monitoring of a super-tall structure using real-time strain data Engineering Structures 67 29
[4] Xiong H-B , Cao J-X, Zhang F-L 2018 Inclinometer-based method to monitor displacement of high-rise buildings Structural Monitoring and Maintenance 5 1, 111-127
[5] Makoond N, Pelà L, Molins C, Roca P and Alarcón D 2020 Automated data analysis for static structural health monitoring of masonry heritage structures Struct Control Health Monit 27 e2581
[6] Castagnetti C, Bertacchini E and Capra A 2016 Monitoring leaning towers by geodetic approaches: effects of subsidence and earthquake to the Ghirlandina Tower Struct Control Health Monit 23 580
[7] Poluzzi L, Barbarella M, Tavasci L, Gandolfia S and Cenni N 2019 Monitoring of the Garisenda Tower through GNSS using advanced approaches toward the frame of reference stations Journal of Cultural Heritage 38 231
[8] Baraccani S, Palermo M, Gasparini G and Trombetti T 2021 A time domain approach for data interpretation from long-term static monitoring of historical structures Struct Control Health Monit e2708
[9] Rusinski E, Moczko P and Odyjas P 2013 Estimating the Remaining Operating Time of Mining Headframe with Consideration of Its Current Technical Condition Procedia Engineering 57 958
[10] Beus M J, Ruff T M, Iverson S R, Hasz W and McCoy W G 2000 Mine Shaft Conveyance Monitoring Min Eng 53 55
[11] Yepin V V, Tsvetkov R V, Shardakov I N 2016 Model updating by deformation monitoring data AIP Conference Proceedings 1785 030035