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Monitoring system for the construction of buildings in the area of mining exploitation impact

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Abstract

Observations of building structures in mining areas, reveal the occurrence of periodic and permanent excessive loading situations. These include ground deformations associated with the extraction of underground mineral deposits. In urban areas, these deformations significantly alter the operating conditions of building structures. For this reason, forecasts of ground transformation and analyses of possible changes in the technical condition of buildings on the ground surface are made in advance, even before mining is commenced. Taking into account previous in-house experience of the observed effects of mining impacts on building structures, an original method of monitoring changes in the condition of these structures has been developed. The aim of the monitoring is to record phenomena that change the operating conditions of the structures. In the developed method, measurements are made quasi-continuously using strain and deflection sensors mounted directly on structural elements. In the mining area affected by the mining operation being carried out in the years 2020 - 2022, and with a further one planned in the years 2023 - 2024, through the extraction of 14 coal parcels, three public utilities of special interest were monitored. The measurement results of deformation changes in the elements allow for an assessment of changes in the stress state of the structures, and the integration of sensors mounted on the structures into a wireless network fulfils the demands for maintaining public safety conditions in mining areas. It also contributes to the analysis of fatigue issues in masonry structures due to long-term multidirectional loads.

Keywords: structure monitoring, deformation measurements, building damage, mining deformation, ground impact

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1 Introduction

Measurement observations of changes induced in building structures due to various ground deformations are significant in terms of scientific research as well as for the practical function of tools designed for direct monitoring of structural conditions [1,2]. Monitoring changes occurring in the structure of a building in real-time is important for the safety of occupants and, in the case of strategic infrastructure, for public safety as well.

As the subsoil and foundations of structures are crucial for load-bearing capacity and safely bearing all structural loads, interactions negatively affecting these key areas can be particularly dangerous. Sources of interactions causing ground deformations can be natural geological processes (e.g., landslides) [3] or man-made forces triggered by human activities. The latter include rock mass deformations caused by the underground exploitation of mineral deposits.

The conventional methods for observing changes occurring in the near-surface ground layers are geodetic surveying. In mining areas, geodetic surveying of ground surface deformations (on measurement lines and scattered points) is compulsorily carried out by the surveying services of mining enterprises. Additional benchmarks are also sometimes located on building structures that require special monitoring. Nowadays, modern satellite measurement technologies (GNNS) and photogrammetric/interferometric methods (terrestrial laser scanning, aerial scanning, radar interferometry) are used (in addition to the so-called conventional ones) for monitoring mining sites [4-8](Guerra F. et al., 2020, Perski et al. 2009, Wang L., Deng K., 2020, Odumosu J.O. et al, 2020, Furst S.L. et al. 2020).

The above measurement technologies can also be used to monitor changes and deformations of building masses. However, observations of this type are characterised by periodicity, resulting from the frequency of raids or the execution of a measurement session. Exceptions are automated total stations or scanning stations that can be programmed to take quasi-continuous measurements.

The Strata Mechanics Research Institute of the Polish Academy of Sciences has developed an in-house method for monitoring building structures, in which measurements are made directly on the structural elements, using sensors selected for the type of change (deformation, deflection), and the measurement is carried out quasi-continuously. A particular advantage of this concept, however, is the ability to integrate sensors from multiple structures, distributed across the mining area, into a single wireless network, allowing remote monitoring of a large area.

This study presents the results of measurements conducted on a testing ground that includes three special-purpose building structures located in an active mining area.

2 Modern methods for monitoring building structures will be discussed

The safety of structures directly fits into the area aimed at developing tools that support effective risk management. Dating back to the early 1980s, the development of direct digital control (DDC) technology and Ethernet as a widely accepted standard for data exchange gave rise to the design of integrated systems [9].

In civil engineering, in the last three decades, structural health monitoring (SHM) systems equipped with control and measurement apparatus have been widely used. Two major trends can be distinguished. The first relates to large-scale projects, for which the need arises at every stage of construction and use to manage risks in the process of maintaining the proper technical condition of the facility and the impact of the facility on the health and safety of users [10]. To this end, the use of automatic monitoring systems, implemented at the stage of investment process planning, design and construction of buildings, has become increasingly widespread. The first systems for continuous monitoring of the static and dynamic response of an engineering object for the detection of anomalous structural behaviour involved bridge structures [11, 12]. These activities are currently being developed as a Graph-Based Digital Twin (GBDT) structure used in maintenance systems for high-rise structures and bridge spans under dynamic actions from wind and earthquakes [13, 14]. Early detection of anomalies and rapid assessment of the level of hazard are fundamental to maintaining the safety of the continuity of a bridge crossing, which is often a primary traffic route.

The second area of development of remote observation methods and systems relates to the supervision of the maintenance of safe load-bearing and service conditions under exceptional loads. One of these includes ground movements of anthropogenic and natural origin. In such situations, measurement observations are made of building and geotechnical structures, as well as the soils that constitute the foundation of the building and the ambient medium of underground structures [15].

The modern challenge of structural health monitoring (SHM) technology is the acquisition of accurate and reliable monitoring data and effective data analysis, developed from lessons learned from practical implementations [16].

3 Characteristics of the research area

The testing ground of the implemented research programme is located in the Upper Silesian Coal Basin, within the boundaries of the Rybnik District. Underground coal mining in the area has been going on practically continuously for about 230 years. The first blasting works were carried out as early as 1792, in the first four mines established in the area.

The observations concern three structures located within one mining area. The measurements carried out as part of this study were initiated in 2020 by setting up two inclinometers on the tower of the Corpus Christi church (Kościół Bożego Ciała) in Rybnik (Structure A). Thanks to the established system for reading out changes in the position of the structure, digital recording and remote transmission of measurement results, changes in the inclination of the structure caused by the mining exploitation carried out in this area have been monitored since 2021. In 2022, measuring equipment was installed on the bell tower of the St. Jack's Church (Kościół św. Jacka) building in Rybnik Radoszowy (Structure B) and the water tower/now viewing tower/ Historic Ignacy Mine in Rybnik (Structure C). All the buildings covered by the measurements in 2022 – 2024 will be within the range of the main influences from the mining of the parcels directly below them. The structures of the buildings will be subjected to dynamic impacts - from the full passage of the extraction front - and to fixed impacts - once the extraction is fully completed. Fig. 1 shows a map of the study area and Fig. 2 shows the location of sections of the mining plots of seams 703 and 713 in relation to the buildings included in the measurements.

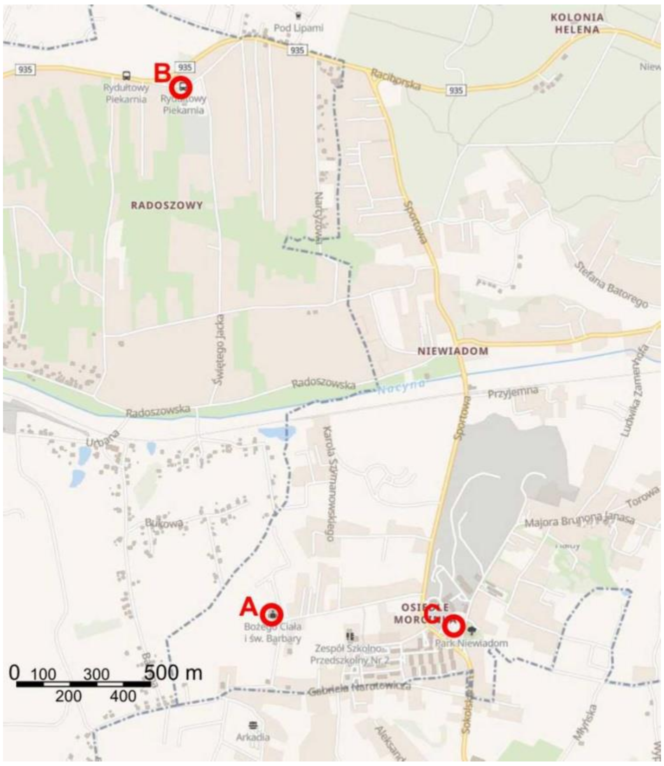

Fig. 1 *Plan of the study area marked on the site map - shows the location of structures A, B and C.*

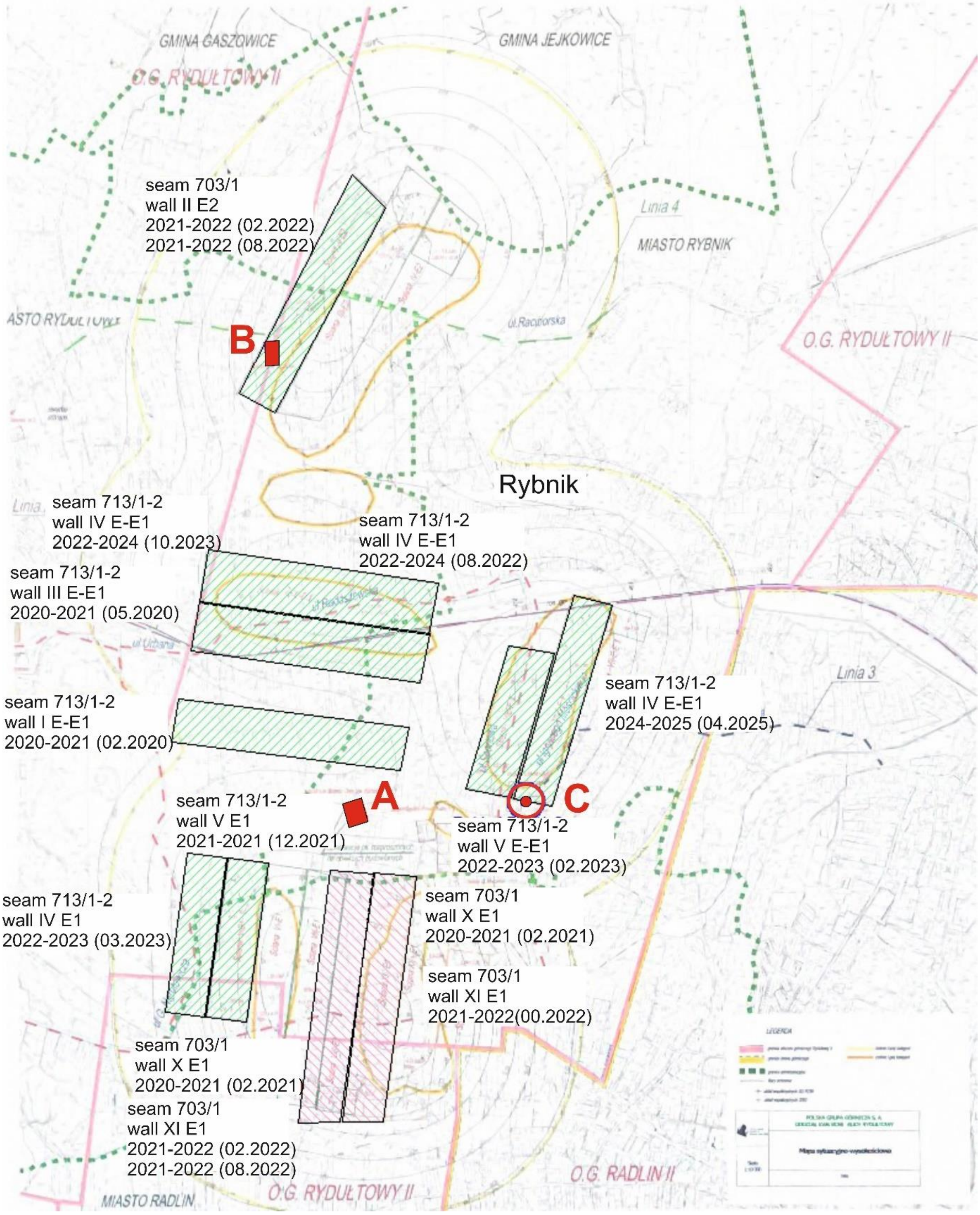

Fig. 2 *Plan of the study area marked on the site map - shows the location of structures A, B and C in relation to the mining plots.*

The testing ground structures will be in different mining situations during the measurement observation period, thanks to which the states of deformation of the structure corresponding to the influence of:

- convexity of the edges of two mining basins - from the influence of the mining plots located outside the structure, on two opposite directions - this concerns the bell tower of St. Barbara Church (Kościół św. Barbary), marked "A",
- full passage of the longwall front - from the influence of the plot located under the building of St. Jacek Church (Kościół św. Jacka), marked "B",

- the convex permanent edge of the mining basin - from the influence of the location of the tower of the Historic Ignacy Mine on the edge of the mining parcel, marked "C".

Structure A – is a free-standing bell tower that is part of the development of the church complex. Architecturally, the tower is connected to the church and rectory building by an elongated pergola (Fig. 3).

Fig. 3 *Structure A of the testing ground* **-** *bell tower, parish buildings visible in the vicinity*

At its highest point, the tower is approx. 15.00 m high, built on a quadrilateral plan with a horizontal projection of approx. 4.50 m × 4.70 m. The tower structure is founded on a slab foundation. The walls up to a height of approx. 4.00 m are reinforced concrete, above that they are clay brick. The vertical cross-section of the structure distinguishes three storeys, with reinforced concrete floors. Additional bracing of the tower structure is provided by a steel frame, made of rolled sections, mounted on two storeys: from the 4.25 to 10.30 m level. The bracing structure was constructed in 2015 as a protection of the building against the effects of mining, after numerous cracks were observed, visible on the external and internal planes of the walls.

Structure B - is a church building, built around 1922 on a single nave plan, with a bell tower on the side of the main entrance (Fig. 4).

Fig. 4 *Structure B of the testing ground - church building, visible bell tower and main entrance*

The length of the church building, including the chancel and vestibule, is approximately 41.50 m, with a nave width of approximately 17.00 m. The height of the bell tower structure is approximately 27.70 m. The above-ground part of the building is built in traditional masonry construction. The foundations of the church are made of rubble stone, the walls of burnt brick with lime mortar. The ceiling over the nave is wooden, suspended from the wooden roof truss. The bell tower is brick in the lower part and wooden in the upper part. The nave side of the tower has a choir balcony, which is of reinforced concrete, supported partly on the masonry wall of the tower and partly on two brick columns. The staircase to the choir and in the lower part of the tower is reinforced concrete; in the higher part of the tower it is wooden, ladder-like. The church structure has been reinforced with a reinforced concrete ring around the nave, external pilasters and internal tie-beams in the ceiling plane.

Structure C - is a viewing tower, opened to the public after the post-mining facilities were rehabilitated (Fig. 5).

Fig. 5 *Structure C of the testing ground - view of the viewing tower after the rehabilitation of the industrial water tower*

The tower structure is the remains of a brick chimney built around 1880. In 1952, as part of an adaptation, the height of the chimney was reduced and a steel industrial water tank was installed on top. The structure served as a water tower until 1994. Today, the tower is open to the public as a viewing point. The core of the tower, made of solid brick, is 35.00 m high. The outer diameter at the base is 6.00 m, with a wall thickness of 1.00 m. At the level of the top of the shaft, the diameter is 4.60 m and the wall thickness is 0.50 m. The tank has an internal diameter of 8 m. The total height of the structure, the tower including the tank, is 45.00 m. Inside the core of the tower, there is an accessible staircase leading to the viewing platform.

4 Methodology, measurement results

The measurement equipment used on the testing ground were tilt meters produced by RST Instruments Ltd., specifically the DTL202B model (Biaxial Digital Tilt Loggers), which utilise MEMS (Micro-Electro-Mechanical Systems) technology. These meters allow for measuring the tilt of an element in two planes. The measuring range of the instruments is ±15º, the resolution: ±0.0006º, non-linearity ±0.002º. The devices have 4 MB built-in memory and a 5-year battery capacity; they allow operation with the RSTAR radio transmission system (distributed sensor topology) and the DT Link radio transmission system (sensor-hub topology). During the measurements on the testing ground, the equipment operated in the sensor-hub topology, with the tilt logger data transmitted to a hub, and then via a USB connection to a computer. The plan is to launch a system that allows for remote reading of measurement data.

The system installed on the structures performs automatic measurements at a user-defined frequency of every 6 hours. The measured quantities are the sine values of the tilt angles in two planes (TILT 1, TILT 2). The sine values are provided with an accuracy of up to 6 decimal places. Proper mounting of the sensor using a custom-made steel bracket (Fig. 6) ensures that the measurement yields the sine values of the tilt angles in the axis parallel and perpendicular to the wall to which the sensor is attached. This enables the determination of the tilt magnitude and the calculation of the tilt vector direction. The measurement readings are then converted into appropriate units, such as angle measurement in degrees or tilt in millimetres per metre [mm/m].

Fig. 6 *Biaxial tilt sensor - visible mounting method using a steel bracket anchored to the wall of the structure*

The initial tilt measurements of the structures were carried out as follows: Structure A - 12 March 2021; Structure B - 7 June 2022; Structure C - 26 April 2022.

4.1 Structure A

Inside tower A, at a height of 8 m measured from ground level, two sensors were installed on perpendicular walls of the tower (Fig. 7). The meter numbered 1230 was mounted to the east wall, while the meter numbered 1229 was mounted to the south wall. The mounting bracket, integrated with the equipment, was fixed to the bricks by steel mechanical anchors.

The used DTL202B tilt meters (Biaxial Digital Tilt Loggers), utilising MEMS technology, were employed on the survey site.

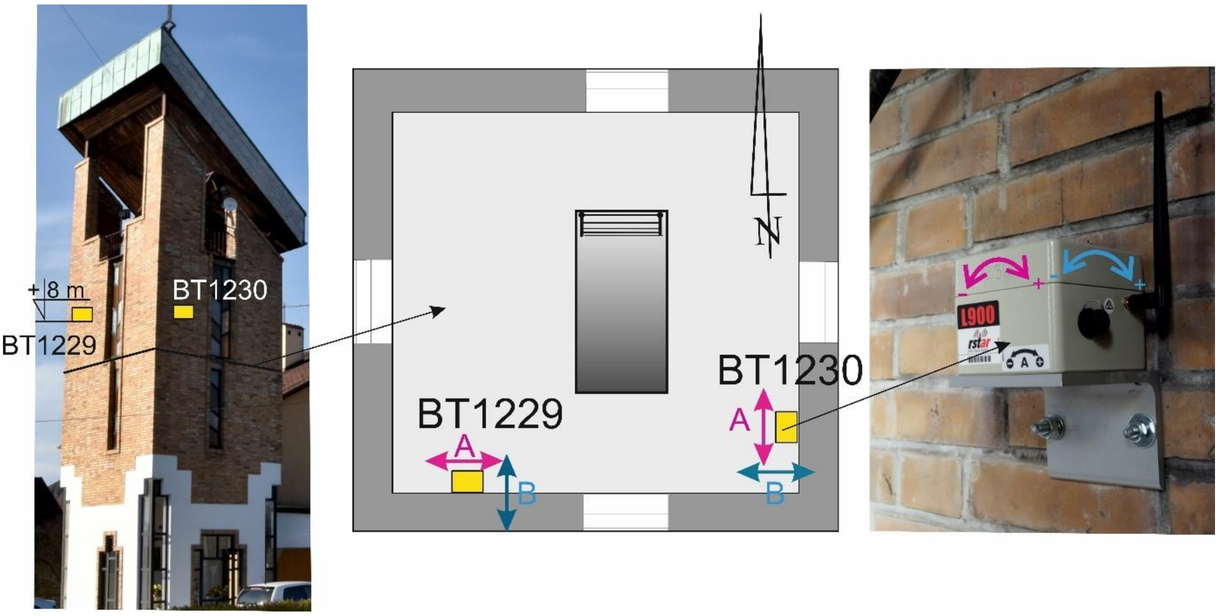

Fig. 7 *Distribution of tilt sensors on Structure A*

Figures 8 and 9 present the tilt magnitudes of sensors BT1229 and BT1230 recorded from March 2021 to October 2022. It is noticeable that the tilt magnitude of sensor BT1229 is significantly larger, ranging from approximately

60.8 mm/m to 61.4 mm/m, while the tilt magnitude of sensor BT1230 is considerably lower, around 10.0 mm/m. This indicates that the tower walls were already tilted before the installation of the sensors, and their planes are not perpendicular. As the tower structure has been influenced by mining activities in the past, resulting in tilting and deformation of the masonry, this observation aligns with the actual condition.

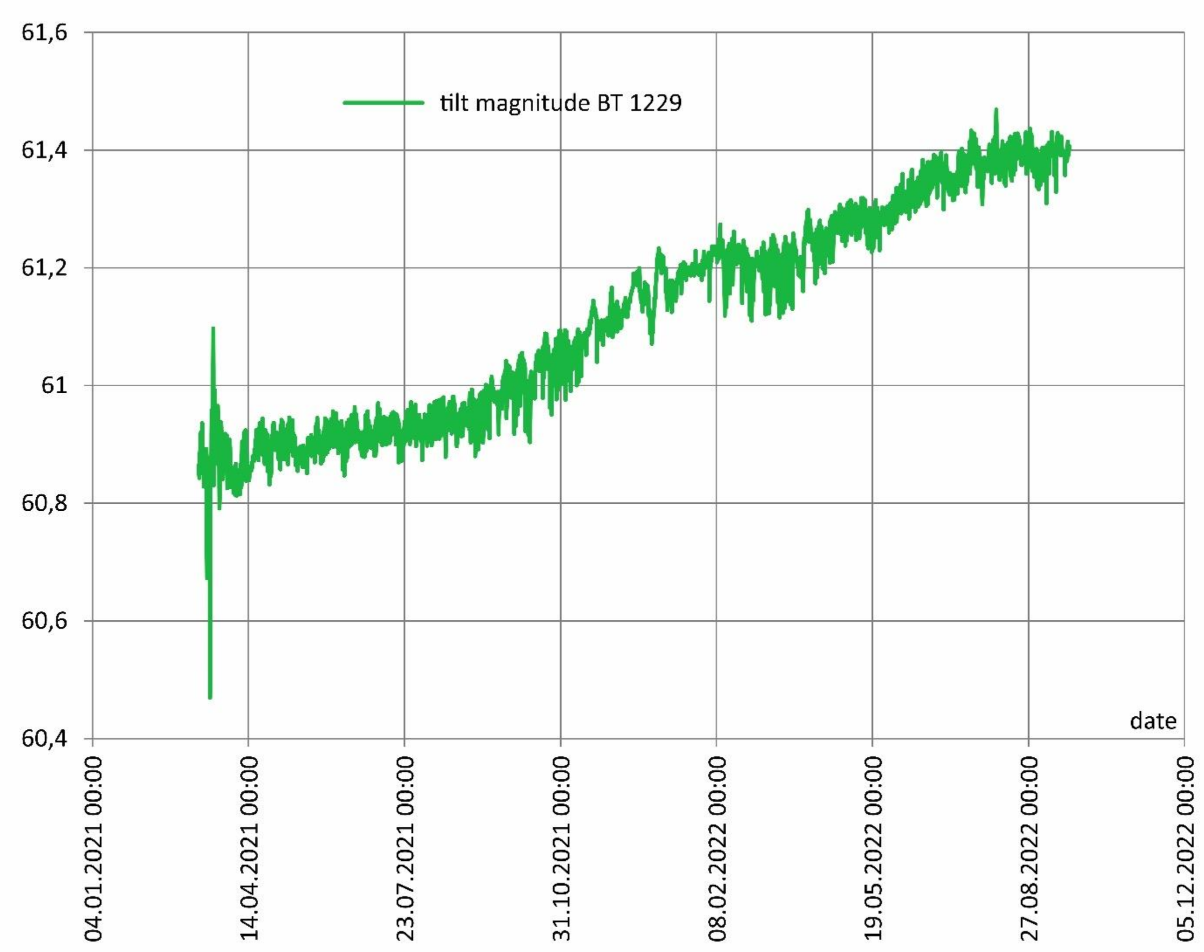

Fig. 8 *Structure A of the testing ground - tilt magnitude of sensor BT1229 [mm/m]*

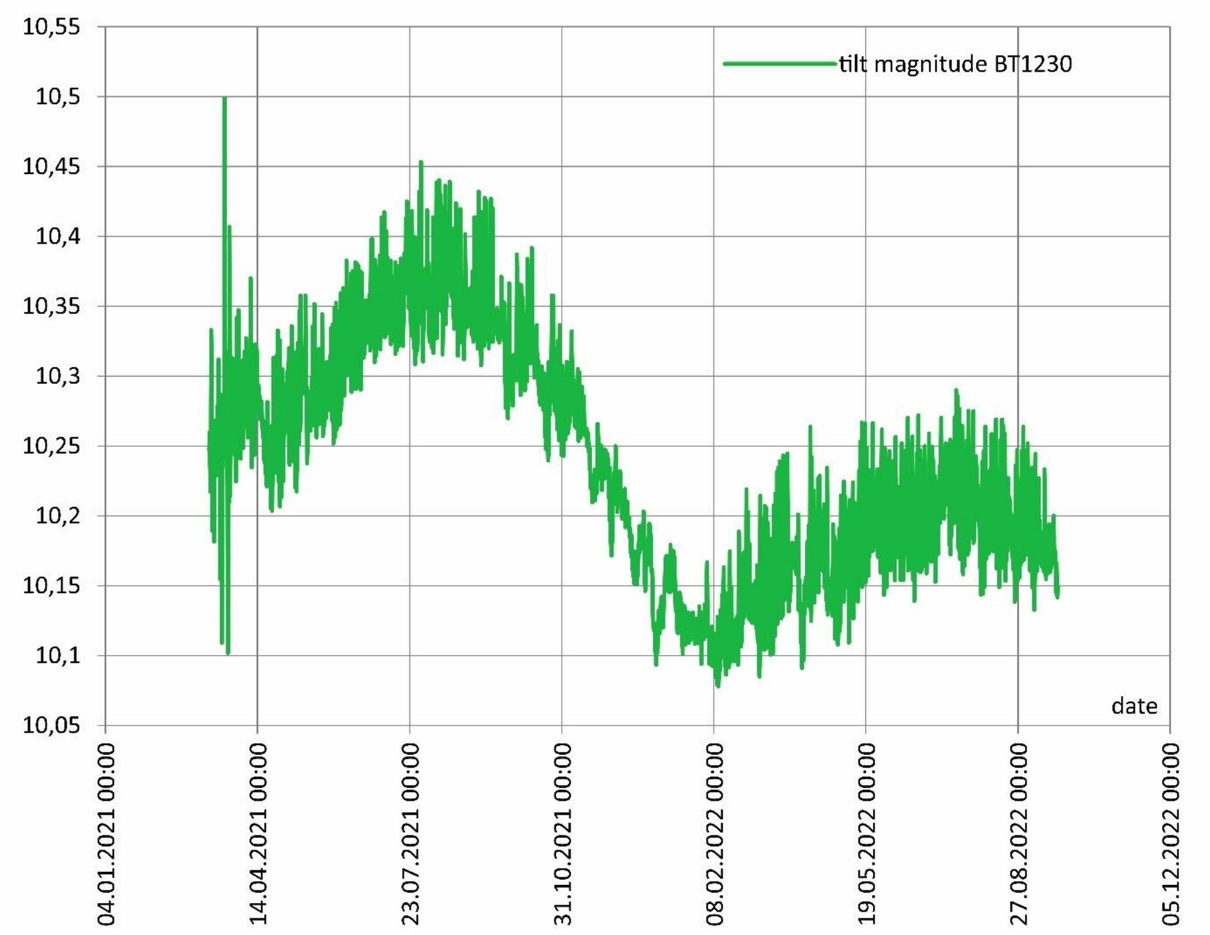

Fig. 9 *Structure A of the testing ground - tilt magnitude of sensor BT1230 [mm/m]*

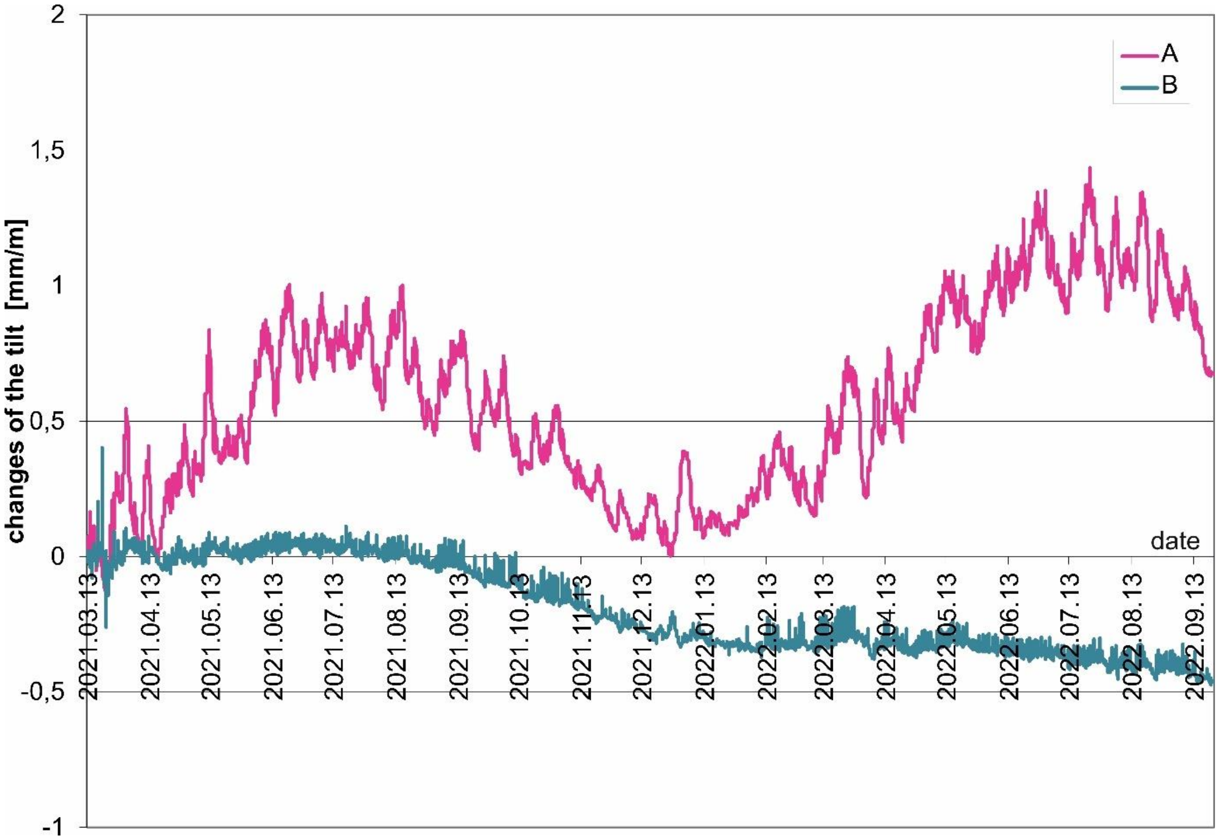

Fig. 10 *Structure A of the testing ground - sensor BT1229, changes of the tilt [mm/m] measured on axes A1: E-W and B1: N-S, from March 2021 – September 2022*

Figures 10 and 11 display the variations in tilt on the sensor axes. Using the measurement results, it is possible to analyse the spatial behaviour of the closed-section masonry structure, which was subjected to mining activities in seams 703/1-2 and 713/1-2 from March 2021 to September 2022 (see Fig. 2).

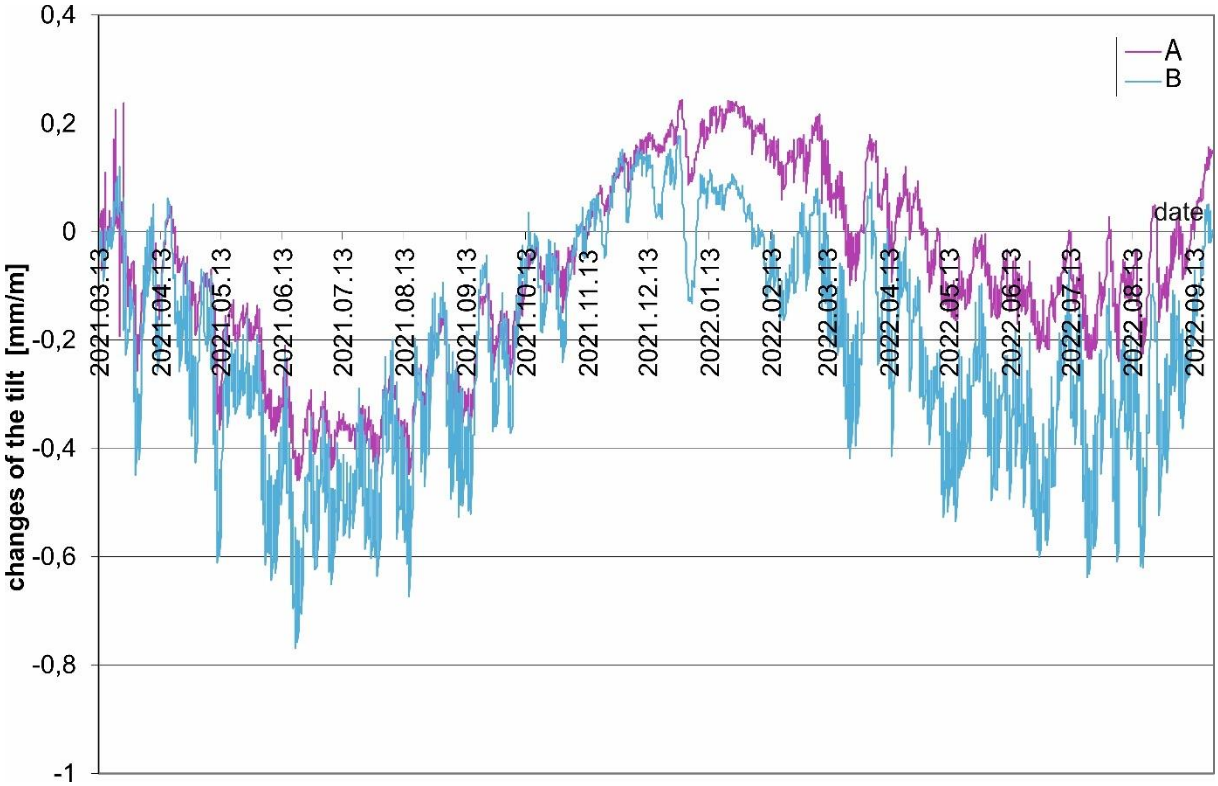

Fig. 11 *Structure A of the testing ground - sensor BT1230, changes of the tilt [mm/m] measured on axes A2: N-S and B2: E-W, from March 2021 – September 2022*

By comparing the measurement results of recorded wall tilts with the location of mining plots relative to the structure, it can be concluded that the main influence during the period from March 2021 to September 2022 came from fields 713/1-2 marked as IVE1, VE1, XE1, and XIE1. In relation to the structure, the predominant direction was southeast-southwest (measurements B1: 0.0 mm/m to 0.5 mm/m; A2: -0.4 mm/m to +0.2 mm/m; B2: -0.8 mm/m to +0.2 mm/m). Recorded on sensor BT1230, the dominant tilt in the N-S direction (measurement A1: 0.0 mm/m to 0.5 mm/m, 0.0 mm/m to 1.5 mm/m) illustrates the influence of mining in field IV-E-E1. A characteristic feature of the measurement results on the sensors is the registration of slight tilt values with changing directions (+/-) over time. For a masonry structure, this means that its geometry undergoes dynamic changes in a short period, affecting stress distributions in horizontal and vertical cross-sections of the wall. This observation is particularly important for assessing the impact of these changes on the disintegration process of the wall, which occurs due to variable directions of influence, even with small magnitudes.

The recorded tilt situation during the measurements represents only a small part of the phenomenon involving prolonged exposure of the tower structure to variable tilting of the underlying mass. Analysis of the mining activities indicates that since the start of mining in this area, the tower has been located on the convex edge, at the junction of two depressions located outside the object, resulting from the exploitation of parcels in an orthogonal arrangement (see Fig. 2).

Analysis of the results shows that the sensors have managed to capture the course of the phenomenon qualitatively and quantitatively.

4.2 Structure B

Measurements on Structure B began in June 2022. The nature of this structure differs from Building A, despite both serving as bell towers. Tower A is essentially a separate structure from the church, while the tower in Building B is an integral part of the church's structure. As seen in Figure 12, it was already tilted due to previous mining activities on the building. The initial tilt magnitude was approximately 15.8 mm/m. The variations in tilt during the observation period are shown in Fig. 13. The recorded values demonstrate a slow deformation process, but the measured magnitudes so far do not pose a threat to the safety of the structure.

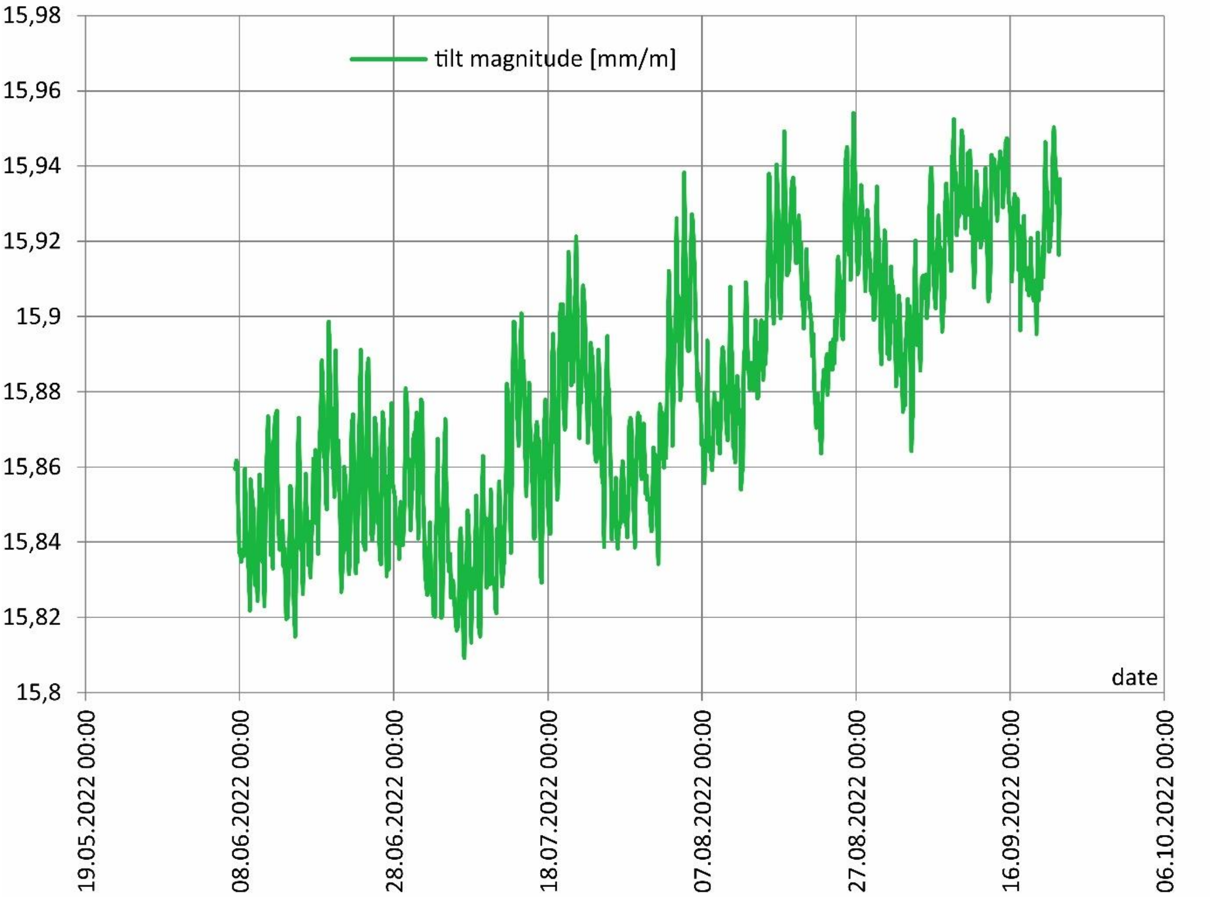

Fig. 12 *Structure B of the testing ground - tilt magnitude [mm/m] recorded on sensor DT050727*

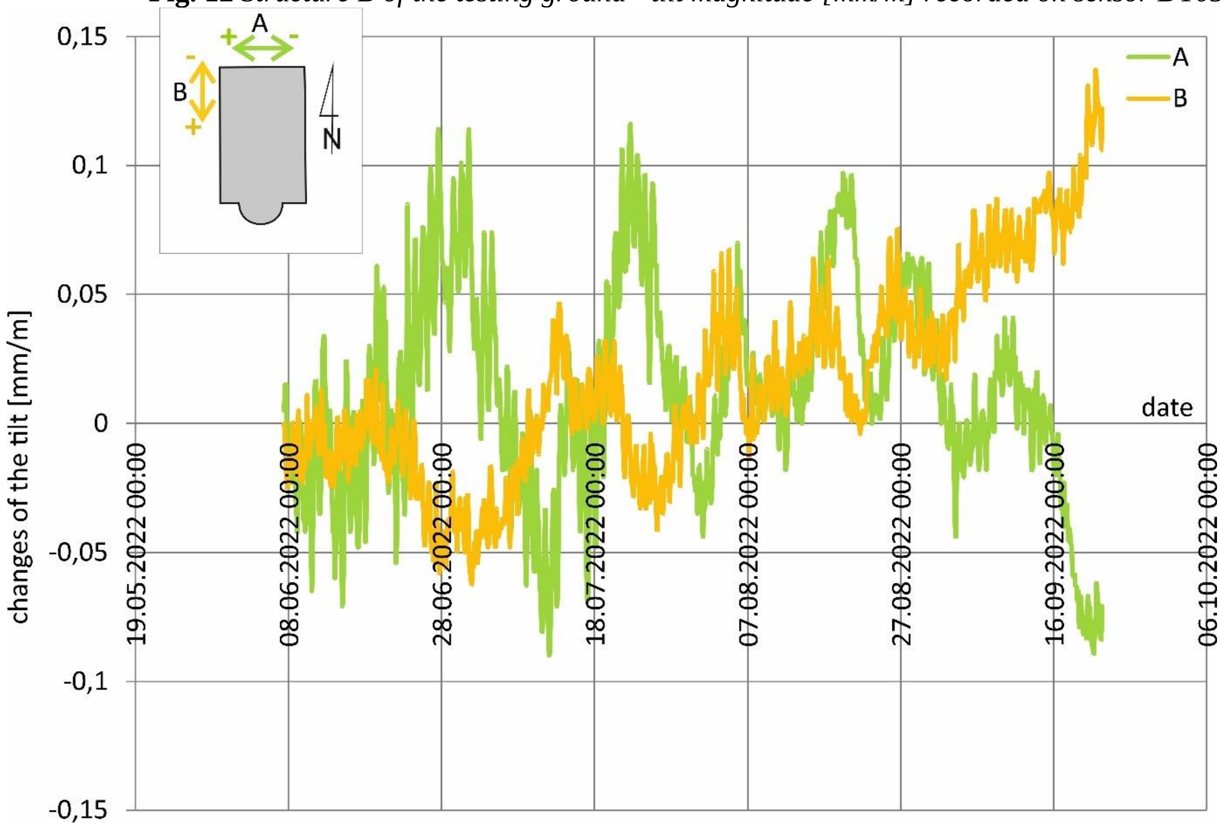

Fig. 13 *Structure B of the testing ground – changes of the tilt [mm/m] over time, sensor DT050727*

4.2 Structure C

In contrast to Structures A and B, the initial tilt magnitude in Structure C does not allow for conclusions regarding previous deformations of the structure, as the walls of the observation tower are structurally inclined and narrow towards the top. Therefore, in this case, only the changes in tilt magnitude during the observation period are considered. The measurements were conducted from April to September 2022. As shown in Fig. 13, in the first two months of measurements, the tilt magnitude increased by approximately 0.4 mm/m. When assessing the structural condition, it should be noted that during the observation period, there was an increase in the displacement of the centre of gravity of the structure in the plan by approximately 14.0 mm.

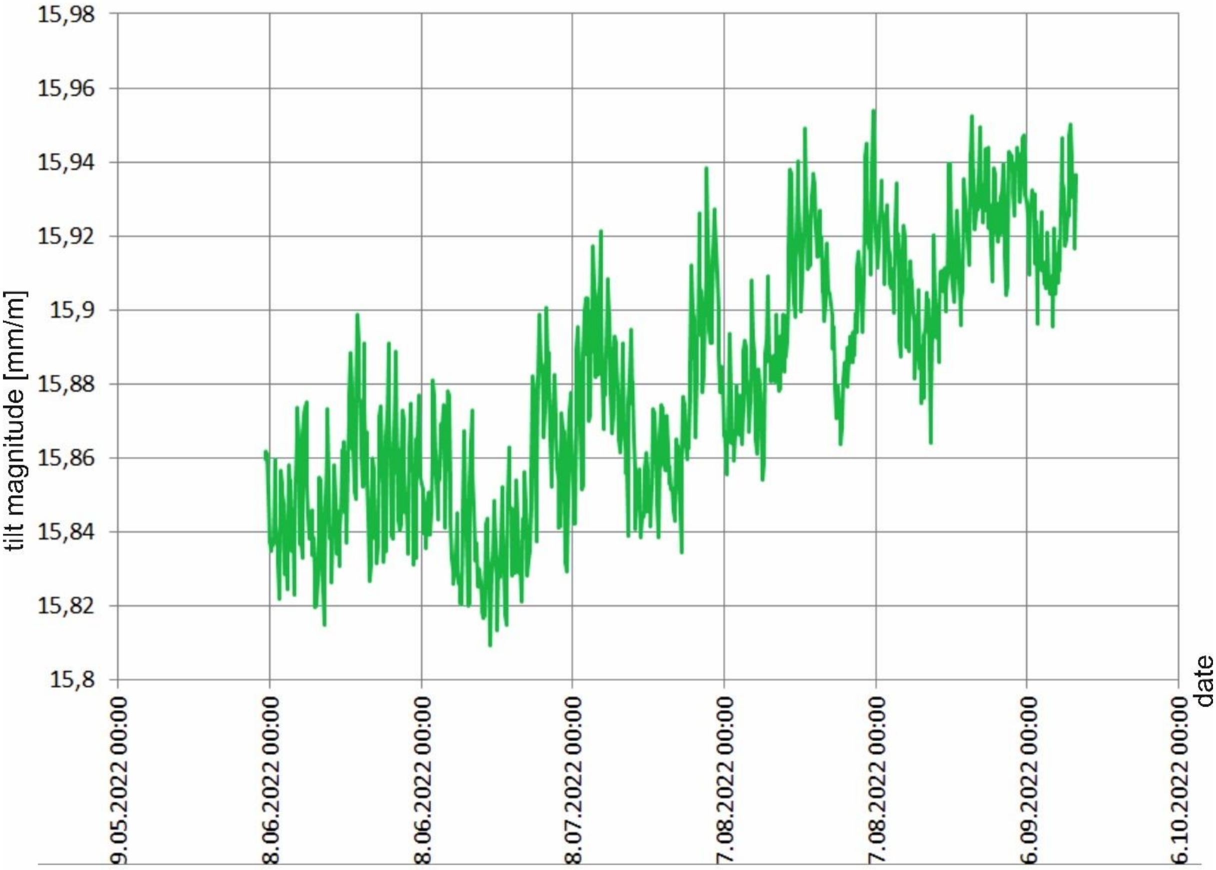

Fig. 14 *Structure C of the testing ground - tilt magnitude [mm/m] recorded on sensor DT2485*

5 Summary

The role of the foundation in a building is to ensure stability and safely transfer the loads imposed by the structural system. However, in the case of buildings located in areas affected by geodynamic or anthropogenic processes that alter the rock mass, the foundation becomes a source of deformative loads for the structure. Expert observations of the sites and measurements using deformation sensors (and optionally, seismic sensors) provide valuable knowledge about the shape and magnitude of the effects on the structure resulting from these interactions.

The presented measurement results demonstrate a method for monitoring the tilts of tower structures located in areas affected by underground mining, which have been and continue to be influenced by substrate deformations. Due to previous deformations, Structures A and B received additional structural reinforcement in the form of stiffening frames. The purpose of the implemented measurement systems is to remotely and continuously monitor the deformations of these buildings, ensuring the safety of their use as public facilities.

As the results have shown, the developed measurement system fulfils its role by enabling quasi-continuous monitoring of changes occurring in the observed structures due to ongoing anthropogenic processes in their foundations. So far, measurements in all structures have demonstrated gradual changes and a lack of threat to the ultimate limit states of load-bearing capacity and serviceability. It should be noted that these conclusions apply only to the areas surrounding the sensors. As mentioned earlier, the measurements are point-based, and their results cannot be extrapolated to the remaining area not covered by the concentration of sensors that ensure the internal integrity of the structural system.

In addition to the installation of the measurement system, all structures have been subject to expert observations through periodic comprehensive site visits. The results of the comprehensive examinations will be published separately. This work is solely dedicated to the results obtained through the measurement system and showcases its capabilities for remote monitoring of the tilts of the structures.

Empirical investigations into the impact of substrate deformations on the deformations of a structure are most reliable when conducted using high-quality measurement systems and involving a team of experienced experts. The role of experts is to properly design the measurement instrument layout and measurement program, identify suitable sensor locations and mounting methods, supervise the measurement process while observing the sensors and areas outside the measurement points, and interpret the results correctly. Therefore, the expert team should include specialists in building construction, metrology, and measurement instruments. A comprehensive understanding of the entire measurement process ensures accurate inference and proper determination of the actual effects of foundation deformations on the building. It is important to note that both the investigated object and the measurement system are subject to various stimuli that can influence the measurement results.

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