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Monitoring of a historic sacral building on an example Basilica St. Nicholas in Gdańsk

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Abstract

The paper describes the case of monitoring the technical condition of a historic sacral building after a failure and during renovation works. In order to monitor the condition of the building, safely conduct diagnostic work, identify the causes of failures and safely carry out renovation works, a detailed Facility Monitoring Program has been developed, which has been implemented, is operational and is a source of valuable data used to assess the current condition of the facility.

Keywords: object monitoring, construction diagnostics, monument, sacral building, failure of a brick building, failure of a monument, Basilica of St. Nicholas in Gdańsk

1 Introduction

Ensuring the safety of the construction and use of building objects is the responsibility of the Owners and Administrators, which are imposed on them by the applicable provisions of the Construction Law [1]÷[2]. This obligation is unchangeable, regardless of the type of building: residential, public or industrial buildings, as well as regardless of their age [3]÷[9]. Meeting the safety requirements is particularly difficult and expensive in the case of historic buildings due to their age and accompanying technical and operational wear [10]÷[23]. Renovation works in monuments are usually limited by the Conservator of monuments to conservation (preservation) works, and construction works are performed to a limited extent, only in cases justified by the destruction of their part or the collapse of the whole. The article describes the effects of a failure that occurred in the historic building of the Basilica of St. St. Nicholas in Gdańsk (Fig. 1a). During the inspection, a crack in the arch between the pillars of the southern aisle and cracks in the vaults of the southern aisle and the central basilica were observed (Fig. 1b). After observing the cracks, under the leadership of the Monastery Prior, a multi-discipline Team of Specialists was formed, which included: the monastery authorities, Monument Conservator, Construction Experts and Architect, Architecture Historian, Art Historians, Geotechnician and Archaeologist.

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2 Preliminary assessment of the scope of defects and damages

In the initial stage of the recognition, a visual inspection of the condition of the Basilica's structural elements was made (Photo 1 and Fig. 1), photographic and drawing documentation of the faults and damages was prepared [24]. Photo 2 and Photo 3 show the photos of the cracked arch between the pillars of the southern aisle and representative damage to the vault rib for the southern aisle. Based on the information collected, it was decided to immediately temporarily support the damaged vaults of the south aisle with temporary supporting scaffolding. The scaffolding was to be placed on the historic floor of the church, which was deformed and locally collapsed. For this reason, local covers were made to check the condition of the subfloor under the floor, in which voids and cavities were found. Preliminary tests of the entire floor in the Basilica were carried out using the GPR ground-penetrating radar [25]. Based on the results obtained, a decision was made to temporarily dismantle the floor within the southern aisle for the duration of the scaffolding operation. Before dismantling the floor, a detailed conservation inventory was made. After dismantling the floor, scaffolding was erected to protect the vaults of the southern aisle (Photo 4).

3 Diagnostic works - tests and measurements

After the facility was secured, a detailed program of diagnostics and monitoring of the facility, developed in cooperation with members of the interdisciplinary team, was launched. The key element was the Program for monitoring the facility during the period of security, renovation and repair [26]÷[29] and conservation works. The monitoring of the facility included geodetic measurements of building subsidence, geotechnical and geophysical surveys of the subsoil, monitoring of the groundwater level in the immediate vicinity of the basilica, installation of feeler gauges and measurement of the width of cracks and cracks, construction and installation of a proprietary automatic measurement system (a network of digital displacement and inclination sensors). Due to the limited volume, only selected elements of the developed and implemented Facility monitoring program are described in the further part of the paper.

3.1 Geodetic measurements

Before the failure, the walls and pillars of the Basilica were fitted with traditional mandrel benchmarks whose position was controlled at irregular intervals. After the failure, new benchmarks and geodetic charts were installed on the walls and pillars of the building, which were tied to the functioning measurement network [30]. Fig. 2 shows the location of measurement points and measurement lines led to benchmarks of the national geodetic network. Measurements are carried out in variable periods, before the implementation of the automatic measurement system, geodetic measurements were made every two weeks, and after the implementation of the system, the frequency of readings has changed - measurements are made every 6 months.

3.2 Excavation of foundations, geotechnical and geophysical research

In order to recognize the type and condition of the foundations of the Basilica, classic narrow-spatial excavations were made. The excavations revealed that the foundations of the building were made in the form of stone pillars, on which brick arches are based, above which ceramic walls and pillars of the building were built [31]÷[32]. The condition of the foundations of the building was different in individual excavations. Based on the inspection, it was found that the stone foundations were placed directly on the layers of load-bearing soils (sands and gravels), under which no wooden piles and fascines were found. The layered structure of the pillars at their height was determined. The foundations were made in three stages, approximately 1.0 m high for each layer of stones (Fig. 3). Boulders and stones are laid on lime mortar, and the external surfaces are clad with clay.

Basic and extended geotechnical surveys of the ground under the building and in its immediate vicinity were also performed. Basic research included geotechnical drilling and probing [33]÷[36] and installation of piezometers, advanced geophysical methods were used for extended research: electroresistance tomography (ERT) [37]÷[39], georadar (GRP) [40]÷[43] and multi-channel surface wave analysis (MASW) [44]÷[45] . Selected results of the above-mentioned studies are presented in Fig. 4, Fig. 5 and Fig. 6, as well as described in [24]÷[25], [31], [46]÷[49].

4 Automatic system for measuring temperature, displacements and inflations

Simultaneously with the works protecting the building structure from collapsing, the *Measurement system* [50] was developed, the aim of which was to automatically measure the deformations (displacements and deflections) of building structural elements selected for ongoing and continuous monitoring. The measurement system was developed in cooperation with and on the basis of devices provided by Leica Geosystems. On the walls and pillars of the building, radio sensors of displacement (D) or inclination (C) based on a wi-fi network have been installed. All sensors included in the system are equipped with an ambient temperature measurement module. Access to the results is possible remotely via the website. The sensors are battery-powered, which makes them resistant to interference and power failures. Fig. 7 and Fig. 8 show the location of the mounted sensors on the projection and cross-section of the Basilica building.

The sensors have been placed on 4 levels of the building: I, II, III, IV. The following sensors were installed on the following levels from the floor: Level I: C10_I, C11_I, C12_I, C13_I, C14_I, C15_I, D17_I and D18_I. Level II: C4_II. Tier III: C2_III, C3_III, C8_III, C9_III. Level IV: C1_IV, C5_IV, C6_IV, C7_IV (Fig. 11). The suffix placed in the name of each sensor indicates the type of sensor (C - inclination, D - distance), the number of the sensor is given with an Arabic number, and the Roman number indicates its mounting level. The sensors have been installed in such a way that the inclination in the longitudinal direction of the building is marked with the A axis in the diagrams, and in the transverse direction with the B axis. (0,0349 mm/m). The measuring range of distance sensors is from 0,05 m to 100,00 m with an accuracy of 0,1 mm. Temperature measurement is possible with an accuracy of 0,1 ^{o}C.

After installation, configuration and commissioning, each sensor reports data to the WISENE Leica measurement system. The collected data were used to determine confidence intervals, warning thresholds (orange alarms) and alarm thresholds (red alarms) for each sensor separately. The limits of the confidence area, i.e. acceptable values of the measured parameters, were assumed as the maximum and minimum values of the indications of a given sensor in a period of 12 months, increased by 5% for the alarm yellow (105%) and 10% for red (110%) (Table 1). The sensors work in a continuous mode, registering displacements and deflections as well as the ambient temperature with an interval of 15 minutes. In Figs. 9÷12 and in Table 1 presents selected, exemplary measurement results from the period of 12 months of 2021. In the graphs, colored dashed lines indicate the adopted alarm levels, and Table 1 shows the extreme values of the measured deflections (min/max).

In November 2021 the strengthening of the vaults of the southern aisle was concreted. Concrete works were carried out in three stages on the following days: stage I: October 28 - ribs in fields 3 and 4, stage II: November 4 - ribs in fields 1 and 2 and stage III: November 29 - ribs in fields 1÷4.

A cracked inter-column arch is based on the F2 and F3 pillars, Fig. 9, Fig. 10 and Fig. 11 show the results of inclination measurements of three selected pillars, F1, F2 and F3, respectively. Fig. 12 shows changes in vertical displacements (settlements) of piers F1 (a) and F2 (b) recorded in 2021. by distance sensors D17_I and D18_I. The charts show changes in the trend of recorded values caused by an increase in the load from the weight of the concrete ribs and the shell reinforcing the arches.

The measurement system developed and implemented allowed for quantitative determination of the impact of the renovation works on the structure of the basilica building. In the analyzed period, deformations of the monitored structural elements of the building, their deflections and displacements were observed, which were caused by periodic changes in ambient temperature as well as changes in the value of applied loads due to the reinforcement of the vaults.

5 Conclusions

Diagnostics of historic buildings is one of the most difficult activities in engineering practice due to the long period and unknown way of their operation, lack of history of repairs, modernization, reconstruction or reconstruction, and construction conservation works. The historic nature of the objects, their high historical value and legal protection make it difficult, and many times make it impossible, to carry out invasive research and measurements.

On the example of the historic building of the Basilica of St. Mikołaja in Gdańsk, which failed, a small, selected range of activities performed as part of the recognition of the building's structural system was presented.

In addition to typical activities such as: open pits, geodetic measurements, boreholes, static and dynamic ground probing, specialized geophysical methods were used: electrical resistance tomography (ERT), ground-penetrating radar (GRP) and multi-channel surface wave analysis (MASW).

As part of the analysis and monitoring of the building's condition, an individual Facility Monitoring Program was developed, on the basis of which an automatic measurement system was built and put into operation. This system works in a continuous mode, collecting important data used to develop a project to strengthen the damaged vaults and foundations of the building. In the future, the collected data will be used to assess the technical condition of the building, in particular the effort of its structural elements.

The analysis of the collected data will make it possible to assess the durability of the building's elements and plan renovation works aimed at preserving the priceless historical values of the Basilica of St. St. Nicholas in Gdańsk.

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Photo 1. Basilica of St. St. Nicholas in Gdańsk: view (*photo by T. Majewski*)

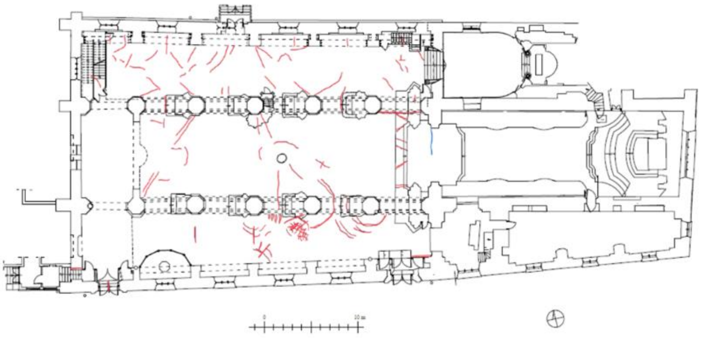

Fig. 1. Basilica of St. St. Mikołaja in Gdańsk: morphology of the features - as of January 19, 2019. [24]

Photo 2. `Damage to the arch between pillars 2 and 3 of the southern aisle of the Basilica of St. St. Nicholas in Gdańsk (*photo by T. Majewski*)

Photo 3. Damage to the diagonal ribs (deformations, scratches and cracks) of the southern aisle of the Basilica of St. St. Nicholas in Gdańsk (*photo by T. Majewski*)

a)

b)

Photo 4. Scaffolding stabilizing the vaults of the southern aisle of the Basilica of St. St. Mikołaja in Gdańsk: a) an arch between pillars no. 2 and no. 3, b) supported ribs of the vaults (*photo by T. Majewski*)

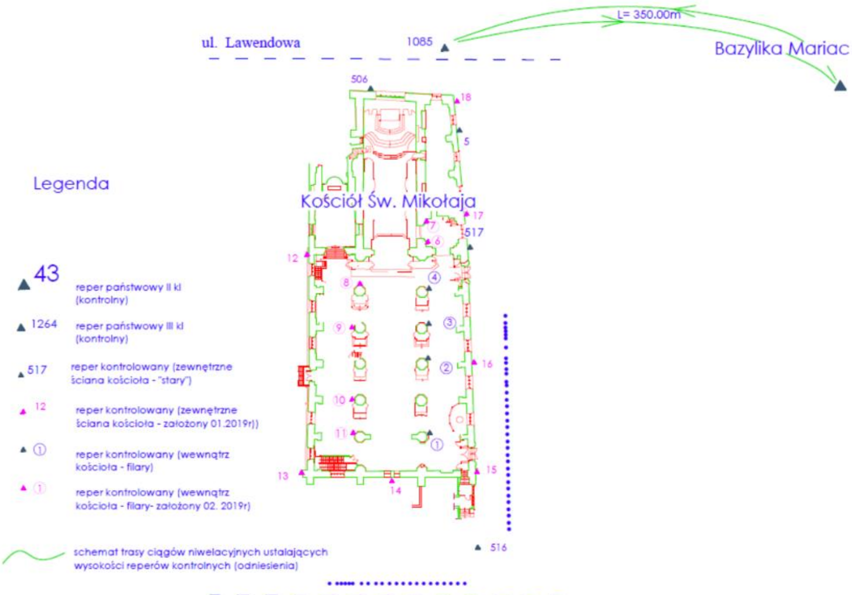

Fig. 2. Location of geodetic benchmarks and measurement sequence in the Basilica of St. St. Nicholas in Gdańsk [30]

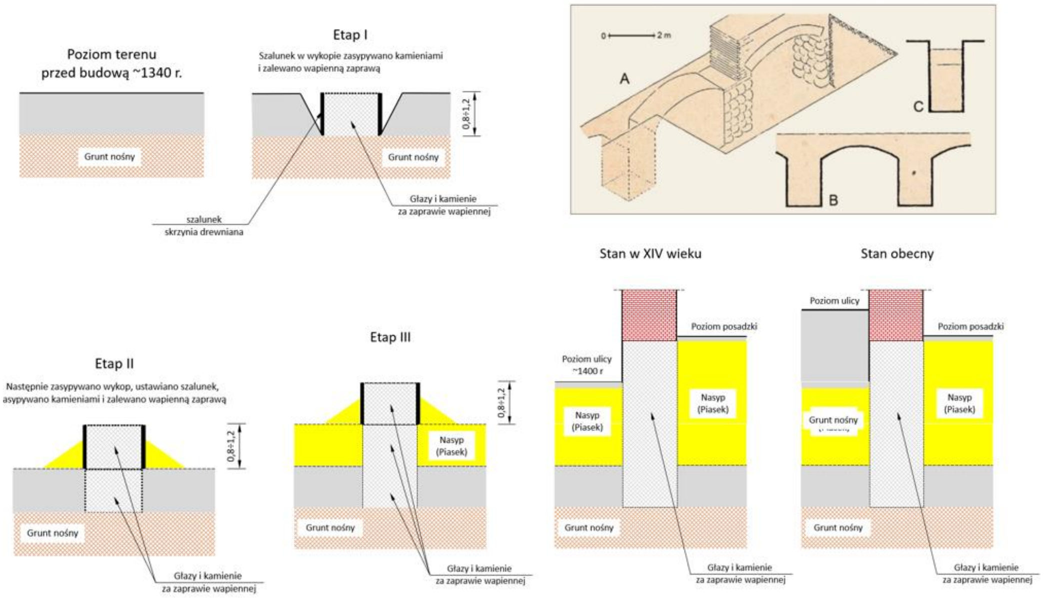

Fig. 3. Foundations of the building of the Basilica of St. St. Nicholas in Gdańsk Basilica [31]÷[32]

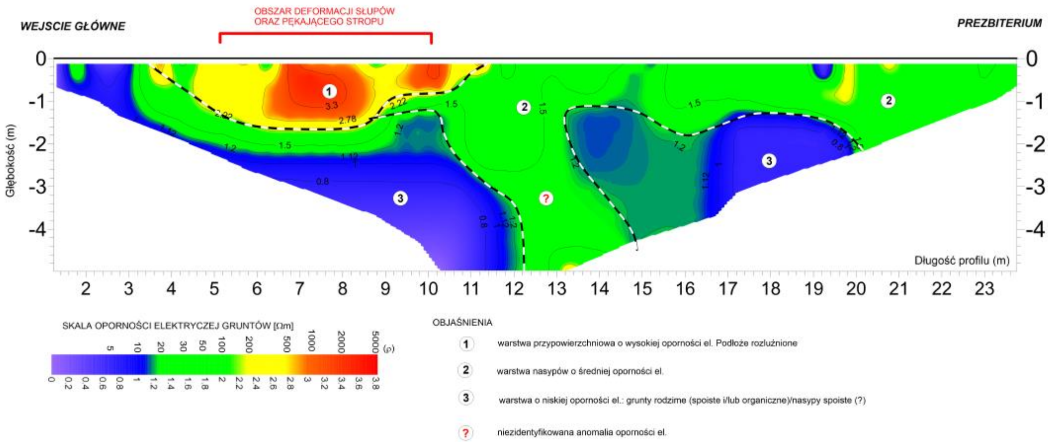

Fig. 4. Electrofusion profile made along the southern aisle of the Basilica of St. St. Mikołaja in Gdańsk based on measurements using electroresistance tomography (ERT) [31]

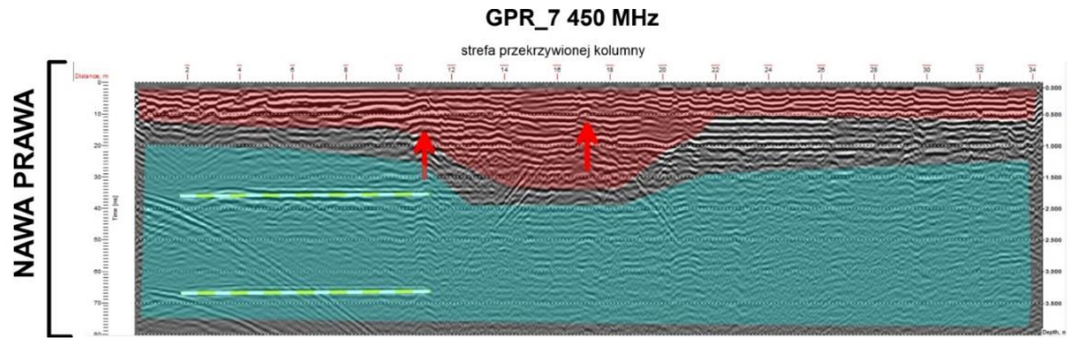

Fig. 5. Selected 450 MHz georadar echogram in the area of the southern aisle of the Basilica of St. St. Mikołaja in Gdańsk based on measurements using GPR [31]

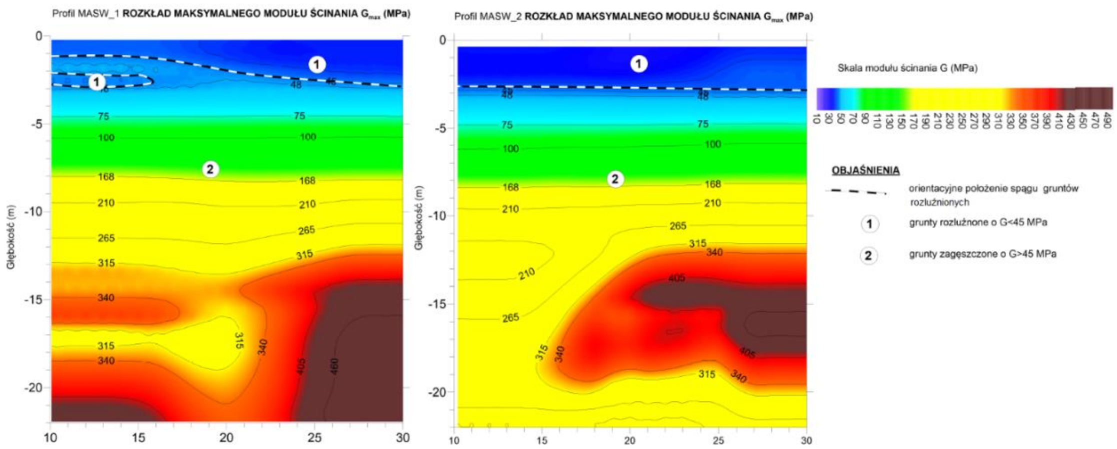

Fig.. 6. Distributions of the *Gmax* shear modulus values in the axes of the southern aisle (left figure) and the northern aisle (right figure) of the Basilica of St. St. Mikołaja in Gdańsk based on measurements using multi-channel surface wave analysis (MASW) [31]

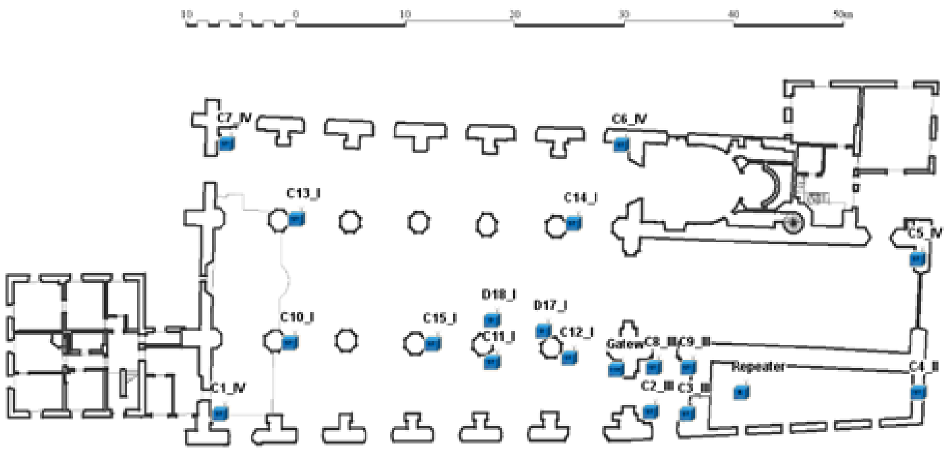

Fig. 7. Floor plan of the Basilica of St. St. Mikołaja in Gdańsk with the location of measuring

sensors marked (*own elaboration*) [50]

Fig. 8. Vertical (longitudinal) section through the Basilica of St. St. Mikołaja in Gdańsk with marked levels of measuring sensors placement (*own elaboration*) [50]

Table 1. Alarm values (yellow and red) of measured deflections for selected sensors

Sensor	Direction	Measurements (100%)		Yellow alert (105%)		Red alert (110%)	
		min	max	lower value limit	upper value limit	lower value limit	upper value limit
C11_I	A	0,0087	1,0158	-0,0417	1,0662	-0,0920	1,1165
	B	-0,5742	0,0489	-0,6054	0,0801	-0,6365	0,1112
C12_I	A	-0,9477	0,1065	-1,0004	0,1592	-1,0531	0,2119
	B	-1,5586	-0,0087	-1,6361	0,0688	-1,7136	0,1463
C15_I	A	-0,3718	0,9879	-0,4398	1,0559	-0,5078	1,1239
	B	-1,1170	-0,1100	-1,1674	-0,0597	-1,2177	-0,0093

a) b)

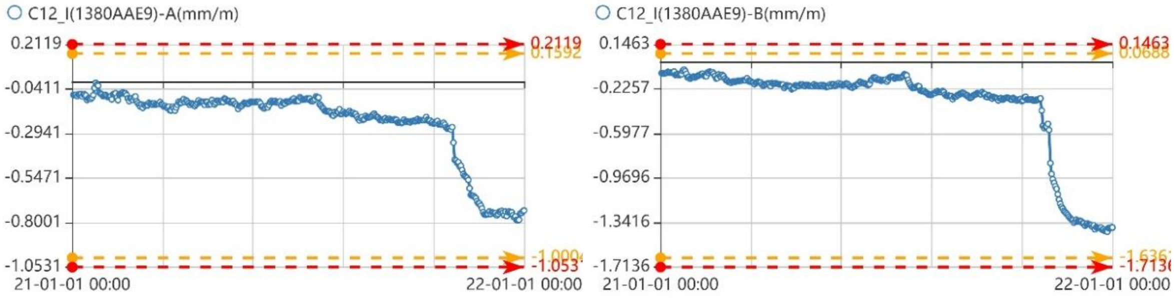

Fig. 9. Inclination of the pillar F1 of the southern aisle in the direction of axis A (a) and axis B (b): readings of the C12_I sensor in the period 01.01÷31.12.2021

a) b)

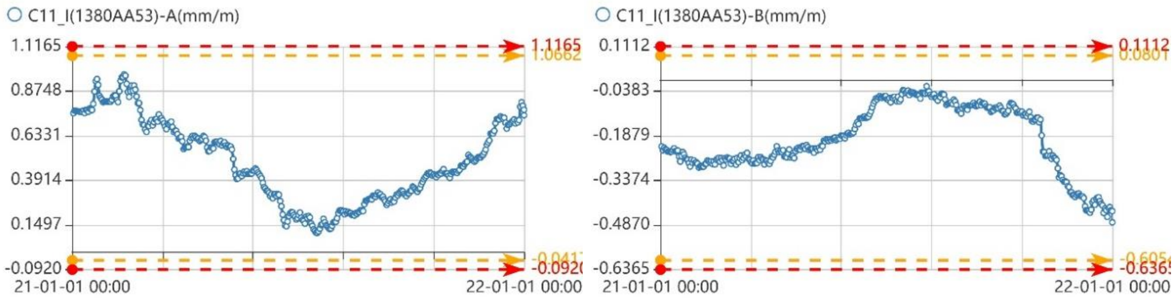

Fig. 10. Inclination of the pillar F2 of the southern aisle in the direction of axis A (a) and axis B (b): readings of the C11_I sensor in the period 01.01÷31.12.2021

a) b)

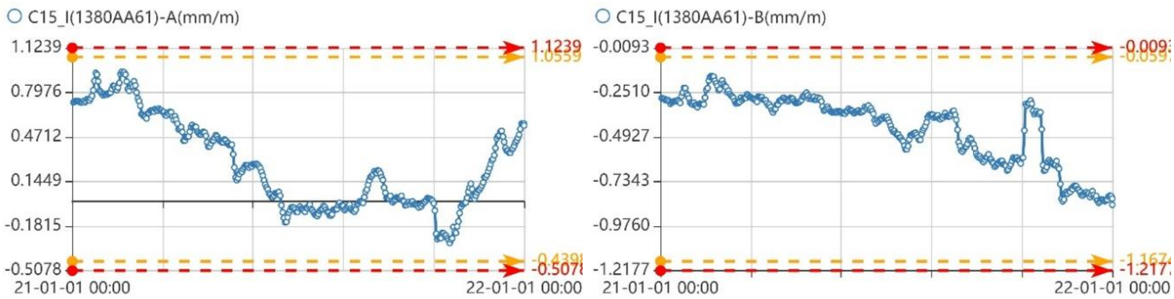

Fig. 11. Inclination of the pillar F3 of the southern aisle in the direction of axis A (a) and axis B (b): readings of the C15_I sensor in the period 01.01÷31.12.2021

a) b)

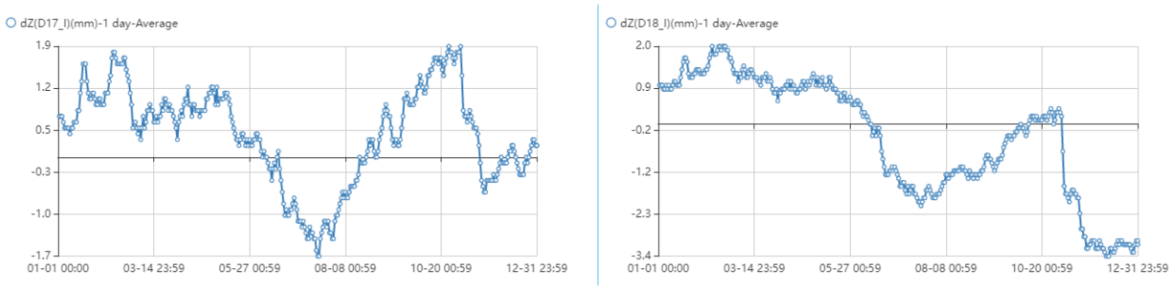

Fig. 12. Vertical displacement of the pillars of the southern aisle based on readings from distance sensors: a) C17_I (F1) and b) C18_I (F2) in the period 01.01÷31.12.2021