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The example of using long-term monitoring and non-invasive measurements for Structural Health Monitoring. Cause study of wall-paintings in St. Anna's Church in Warsaw.

Katarzyna Górecka[1], Sławomir Łapiński[2]* and Jakub Markiewicz[2]

[1]Academy of Fine Arts in Warsaw, Faculty of Conservation and Restoration of Works of Art; katarzyna.gorecka@cybis.asp.waw.pl

[2]Faculty of Geodesy and Cartography, Warsaw University of Technology, Pl. Politechniki 1, Warsaw 00-661, Poland; slawomir.lapinski@pw.edu.pl (S. Ł.), jakub.markiewicz@pw.edu.pl (J. M.),

Corresponding Author: slawomir.lapinski@pw.edu.pl, Tel.: +48-22-234 7287

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Abstract: Heritage objects are affected by many factors that affect degradation over time and damage to historical sites. For this reason, it is necessary to carry out continuous monitoring using non-invasive techniques for Structural Health Monitoring and plan the conservation works. This article aims to present the results of a project that involved long-term monitoring using surveying techniques such as precise tacheometric measurements, precise levelling, inclinometric measurements and crack measurements using crack gauges. This paper presents the results of multisensor monitoring of displacements and cracks in the building, which contributed to the conservation efforts and prevent works. A research object is St. Anne's Church in Warsaw. It is one of the few in Warsaw that wasn't destroyed during World War II.

Keywords: architectural documentation; displacements; heritage at risk; non-invasive techniques; prevent; rescue conservation

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1. Introduction

Nowadays, cultural heritage objects are exposed to different factors that cause their deterioration and degradation over time due to human activities and environmental factors [1,2]. For that reason, it is necessary to perform rescue/prevent conservation works that allow for keeping cultural heritage objects and sites in good shape and condition for future generations.

Architectural monuments such as buildings or small architecture are affected by degradation processes and degradation rates depending on the characteristic of used materials, the object's age and some random events [1]. Very often, the damage is caused by physical phenomena (e.g. deformations and displacement of the ground where the building is located or changes in hydrographic condition and vibrations). This might contribute to scratches, cracks, disconnections, crushing, leanings and moisture, which significantly affect the building's structural health behaviour [3,4].

To monitor the gradual deterioration of antique buildings and their decorative parts such as frescoes, wall paintings, etc., different measurements techniques (classical surveying, photogrammetry, remote sensing, electromagnetic spectroscopy, etc.) [5] and comprehensive analysis (structural health monitoring analysis, operational modal analysis) [6–11] are commonly used. When proper methods of conservation, maintenance of cultural heritage objects, and establishing a schedule of conservation works, it is necessary to identify the factors affecting the degradation of the object. The guidelines from the theory of cultural heritage protection, frequently called conservation doctrine, are the basis for setting design standards referring to work in architectural monuments. Such a preliminary formulation of the rules was *The Venice Charter for the Conservation and Restoration of Monuments and Sites* - an international convention signed in 1964 by specialists from different European countries. Venice Charter recommends that all the activities performed in architectural monuments ensure their further survival together with a complete range of their historical and artistic values, as well as the preservation of authentic substance devoid of contamination or deformation, to pass them on to the next generations. Already then, the principles of the methodology of conservation of works were created. Their content is limited to the main seven assumptions: (1) PRIMUM NON-NOCERE rules, (2) principles of maximum respect for the original substance of the monument and all its values (tangible and intangible), (3) rules of minimum necessary interference (refraining from unnecessary actions), (4) the principle according to which it should be removed (and only what) has a destructive effect on the original, (5) principles of legibility and distinguishability of interference and their aesthetic subordination to the original (uncompetitiveness), (6) principles of reversibility of methods and materials and (7) rules for carrying out all work to the best knowledge and at the highest level [12].

Each object requires an individual conservation approach, and the planned works have the character of an extensive conservation project. The contemporary theory of conservation-restoration is, therefore, not a rigid corset ordering blind adherence to one line of conduct. Quite the opposite - it opens a wide field for individual actions and creative search for optimal solutions. The basis of the conservation project is to recognise the object technic and technology, its history, function and content, and to assess its state of preservation. In exceptional cases, it is necessary to formulate an assessment of the degree of threat - which implies the need for rapid action (rescue work) or if there is no direct danger indication for prevention.

This article presents a top-to-down methodology of integrating rescue/prevent conservation works and non-invasive measurements. The article shows an example of the documentation, architectural and conservation work carried out in St. Anna's Church in Warsaw since 1949.

This article presents the methodology of wall paint conservation works concerning not only the small area of investigation but a whole monument. The scope of pre-project work concerning architectural monuments should include the following:

(1) initial identification of the monument,

(2) measurement and complex inventory of building with details in the form of vector drawings, cross-sections, 3D models and orthoimages,

(3) complex historical research (historical study and architectonic research, and possibly archaeological if approved by Monument Conservation Office) complete with evaluation and conservation guidelines for the whole building and its spatial−functional layout,

(4) complex conservation research of the state of preservation of historical substance of the monument and decorative elements together with defining their structure and technological properties (with simultaneous identification of erosion and corrosion factors such as dampness, salinity and pests) complete with conclusions and guidelines for particular elements,

(5) defining the technical state of preservation of the building (construction assessment or measurement of displacements by expert) with conclusions and construction guidelines considering conservation issues,

(6) geological research of the ground (by a constructor or art conservator if necessary and

(7) research program concerning wall painting as a separate issue [13].

In Section 2 a short overview of the conservation/protection works and structural health monitoring methods were presented. In Section 3 the description of the proposed methodology of integration of the rescue/prevent conservation works and non-invasive measurements were presented. The results of the performed experiments and a brief analysis and interpretation are presented in Section 4. Section 5 contains a discussion concerning obtained results and proposed methodology, and in Section 6 the future works and critical summary are provided.

2. The rescue/prevention conservation works with non-invasive measurements techniques for wall painting protections

Long-term monitoring and measurement should be done to decide if rescue or prevention conservation works should be performed. As a result of that investigation is appropriate and accurate documentation that depends on the aims and scopes of conservation works as well as on the possibilities and limitations of applied measuring techniques. Unfortunately, there is no versatile standard or one methodology for architectural documentation and different national or international organisations, such as the International Committee of Architectural Photogrammetry, The London Charter for the Computer-based Visualisation of Cultural Heritage or national organisations, such as the National Heritage Board of Poland, prepare their regulations [5,14–17]. Due to this fact, the form, quality and resolution of the final architectural documentation for conservation works depend on the proposed methodology of conservation works [18].

The authors decided to present a problem concerning wall paintings due to the wide range of possible conservation work. The specificity of the works of wall painting results from their close connection with architecture, and this dependence concerns the form, subject matter and function, technique and technology of execution, and the state of the preservation. What are the threats to wall painting monuments? Most of them result from the state of the building structure and its interior conditions. The instability of the monument construction is associated primarily with the settlement of the building and hydro-geological conditions of the area; it can also result from defects in the building's structure. Therefore, conservation works on wall paintings should be preceded by expert opinions on the state of the building. For this reason, the procedures for the conservation of wall painting are often associated with activities related to the architecture itself.

In conservation practice, there is quite a lot of freedom in implementing the research programs of painting decoration. Their scope depends on the specifics of the object. The usual workflow is simple; however, the research methods have become more accurate and extensive [19]. There is a need to systematise the research methodology for wall painting, understood as a definite, reliable system of rules and procedures on cognitive activities that

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allow accurate recognition of the history, significance and threat of a given object, which will be the basis for planned conservation solutions [20].

2.1. Measurement and documentation of the painting surface

The combination of documentation from 3D shape reconstruction and remote sensing methods could be used to prepare the conservation project and estimate the cost of the works. In the first step of planning the conservation works, it is necessary to determine the shape and size of the investigated monument. Commonly, dimensions of the wall decoration were usually obtained from the architectural plans, sketches and cross-sections, 3D models or orthoimages of the buildings or calculated approximately "in-suit" [12,13,18]. Nowadays, for 3D shape and reconstruction, non-destructive active and passive techniques are used, due to the rapidity of data acquisition, high accuracy and way of reality representation [21–24]. The passive 3D shape reconstruction methods, especially range-based methods, namely Terrestrial Laser Scanning (TLS), and the Structure-from-Motion (SfM) combined with the Multi-View Stereo (MVS) approach, allow for digital reconstruction of the object with the required accuracy and high level of detail. Due to the limitations of both measurement techniques, it is advisable to perform data integration, which enables the generation of correct geometric and radiometric documentation and improves the accuracy of historic object inventory. Thanks to modern 3D reconstruction techniques, it is possible to measure the curvature of the surface and create 3D models of wall paintings. According to the official polish requirements, surface measurements are carried out before and after conservation work [13].

The measurement and preliminary photographic documentation of the painting surface are obligatory and necessary to prepare the conservation project and estimate the work cost. Dimensions of the wall decoration were usually read from the architectural plans of the buildings or calculated approximately "in-suit". This step is carried out thanks to modern measurement techniques using data extracted from 3D models. Despite this, it is essential to carry out photographic documentation, which should contain a general view of the interior and photos of the painting details.

2.1.1. The iconography of the painting's decoration

Conservation and restoration work should be accompanied by fully recognising the iconographic content and sacral meaning. Research is conducted by analysing archival materials and a query in art history. In the case of ancient painting, presented scenes most often belong to a specific canon. One of the purposes of the research is to find direct graphic prototypes of painted scenes and ornaments. In recent years the study has facilitated gratefulness for online access to iconographic sources. Sometimes the elements of the painting composition are not a direct repetition but a mirror image of the original pattern. Inventory, metric photographs or 3D models of painting compositions allow accurate comparative studies. Recognition of the subject and interpretation of the wall decoration meaning is necessary for restoration works involving the reconstruction of the lost painting fragments.

2.1.2. Identification of the stratigraphy. Research on the painting technique and technology

Diagnosis of the stratigraphy - the arrangement of historical layers in the object, is a key study in the conservation methodology of wall painting. The architecture was transformed over time: reconstruction, expansion and stylistic changes. Wall painting and architecture had to undergo these transformations [25]. The wall decoration could be painted over, changed, and renovated many times; therefore, in one historic building restorer deal with many paintings from different periods. Some appear side by side, but one covers the other most often. Thus, the oldest preserved paintings could be found under many later layers: plaster coatings, lime

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layers and other paintings. In that case, wall decoration is a kind of palimpsest of different layers of paintings. That is why it is so important to correctly recognise the stratigraphy of the layers and associate them with the object's history. Such tests are carried out by making stepped probes and stripe cleaning tests (exposing subsequent layers with a knife or scalpel). The samples of the cross-section are also taken for microscopic examination. In order to recognise the painting technique, pigments and paint binders should be identified by non-invasive tests and microchemical analysis.

Undoubtedly, creating 3D models based on conservation research showing changes in the painting decoration of the interior is the future of documentation and inventory of historic buildings.

2.2. Evaluation of the state of preservation of wall painting – Structural Health Monitoring

Assessment of the object's condition and identification of its damage causes is necessary to formulate the program of conservation works. Most of the dangers for wall paintings result from their close connection with architecture. Structural cracks in the walls are one of the most severe threats, which could consequently lead to the object's destruction. The destabilisation of the building structure causes: cracking, delamination and detachment of plasters from the support, their disintegration, losses of adhesion and cohesion of the painting layers and flaking of the filler. Performing continuous measurements and 3D mapping of the surface of the painting can act as a building and cracking monitoring system.

Nowadays, many monitoring systems track structural systems' behaviour over their complete life cycles to assess their long-term performance and health (i.e., structural health monitoring (SHM)) exists. These systems are made of many different types of sensors; for example, microelectromechanical systems (MEMS) sensors were beginning to be marketed that miniaturised sensor packages, sensing technologies included fibre optic sensors, wireless sensors, piezoelectric surface sensors, vibration-based damage assessment methods to assess the health of offshore platforms and aerospace systems [26]. To enhance the sensitivity of damage detection methods to identify the location, type and severity of structural damage, non-destructive detection techniques (NDT) such as impact echo, magnetic particles, ultrasonic inspection, acoustic emission, thermography, and ground penetration radar, to name just a few, have been considered for use in SHM systems [27,28].

The simple and frequently used solution in SHM is displacement measurements, which are based on the surveying methods such as laser rangefinders, total stations and precision levellers, or GNSS measurements. Another example is the use of inclinometers, which indirectly provide information on displacements understood as translations by measuring changes in angle [29].

The displacements in the building structure result in the appearance of cracks. Cracks are subjected to monitoring to determine the magnitude of their changes and an inventory with the determination of their location in the building. For this purpose, it is possible to use, among others, methods based on the classical photogrammetric approach and TLS [30]. On their basis, it is possible to generate high-quality and high-resolution 3D models or orthoimages. Integrating the 3D model with TLS or multispectral intensity sensors makes it possible to analyse not only the shape but also the condition of the object under investigation [31].

At any stage, crack width can be measured; sometimes, it is necessary to determine whether they increase over time. Simple methods for measuring cracks exist, i.e. glass tell-tales to observe the rate of widening of a crack and to measure the extent of widening with time or the sensors described earlier. In addition to the undoubted advantages of these devices, special installation requirements that are difficult to meet in historic buildings should be noted. For

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safety reasons, some of these devices cannot be used in public buildings without special safeguards. In addition, there are several restrictions on surveys in historic buildings due to difficult access to the building or individual architectural details and the impossibility of using permanent measuring point distribution [32]. In many cases, decisions to monitor cracks in historic buildings are made on an emergency basis.

Moisture is another dangerous factor for wall painting. It could be caused by direct water infiltration or condensation of moister from the air on the painting surface. Persistent moisture leads to changes in the painting colour which become darker. The phenomenon can be observed even in the painting fragments executed on the heterogeneous wall (made with stones and bricks) whose weft elements unevenly release moisture. Therefore, the condition of the building foundations (threatened by the capillary rising of groundwater), the tightness of the roof and windows, the patency of drainage systems and the state of the installations should be assessed. Maintaining a constant humidity and air temperature is also extremely important for the painting's condition. In diagnostics of moist areas of the wall painting, a thermal imaging camera could be used, which allowed for obtaining a temperature image of the whole surface. The principle of the test is simple, i.e. humid places always remain cooler. Another technique that allows to analyses the in-wall moisture is microwave spectroscopy. Microwaves can propagate through the dielectric material and interact with the material to produce information about this material. Martínez-Garrido et al. [33] published a comprehensive study for moisture control in cultural heritage using several non-destructive techniques, which included an Electrical Conductivity meter (EC) [34], Infrared Thermography (IRT) [35–37], Electrical Resistivity Tomography (ERT) [38–41] and Ground-Penetrating Radar (GPR) [42,43].

3. Materials and Methods

The aim of this article is to present the long-term monitoring and integration of the rescue/prevent conservation works and non-invasive measurements of St. Anne's Church in Warsaw. St. Anna Church is one of the few in Warsaw that wasn't destroyed during World War II. Due to its location, the building has constantly been exposed to structural problems caused by the subsiding of the Vistula escarpment. The internal structure of the escarpment is formed by clay deposits, which strongly absorb water in the spring, change their volume and become plastic. Figure 1 shows the timeline of the SHM workflow and analysis.

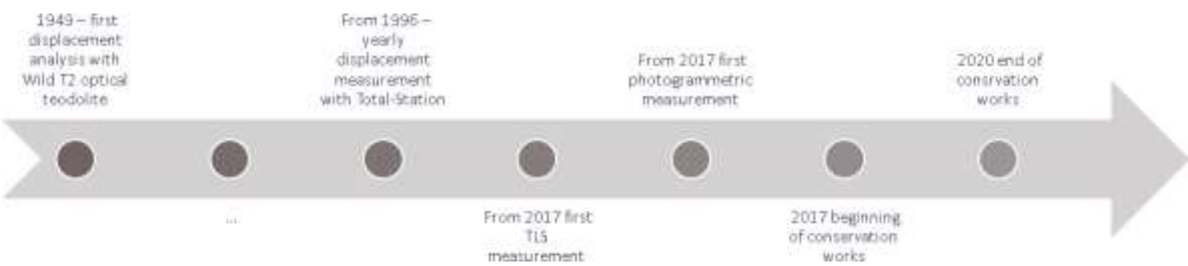

Figure 1. The Structural Health Monitoring analysis and measurements were performed between 1949 to 2020.

In April 1949, horizontal displacements of the Church's tower and its surroundings were determined using trigonometric measurements, and vertical movements were identified using a precise levelling method. Then, the ground around the building was reinforced with columns, and a concrete wreath encircled the foundation. Ground displacement occurs about 25 m deep into the ground. In the '50s, the slope stability was disturbed during the construction of the WZ

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(East-West) road running along a tunnel close to the Church and over the bridge to the other side of the Vistula.

In 1996, it was decided to start monitoring bone displacement annually using tachymetric and precision levelling methods. This was prompted by the occurrence of significant cracks and landslides in the building.

In the years 2010 - 2013, some brick elements got loose in the widow lintels, and dangerous delamination of the plaster on the north wall was observed. The rescue works were undertaken on the church nave's northern wall in December 2013. New cracks on the vault and walls have also been noticed recently.

In 2017, The Rescue Project was undertaken in the Blessed Ladislas' chapel. The chapel, due to its spatial disposition - location from the escarpment side at the north wall of the church nave, belongs to the most endangered architectural fragments. Since 2017, it has been decided to use measurements using terrestrial laser scanning and photogrammetric methods to fully analyse the shape of selected parts of the Church.

The chapel walls on the east-west axis have been cracked several times in the past due to the instability of the church foundation. A severe structural rupture fragmented the stone base of the lantern. Its loose elements threatened the safety of the faithful and visitors. Therefore, in the early XX-th century, its construction was tied with an iron clamp. In the dome, the cracks ran along the northeast direction according to the movement of the slope. In the southern part of the bowl at 1/3 of its height, the upper part of the plaster was cracked and detached from the brick support. The chapel walls were repaired several times so that the next putties and retouching overlapped in many places.

The mural paintings of the chapel were renewed at the beginning of the XX-th century by painters, who "in memory" scratched their names on the dome walls. They totally repainted the original XVIII-th century composition, probably by using a tempera binder. After World War II, the over-paintings were taken out with soda lye compresses. Unfortunately, during that treatment, the original Żebrowski's polychrome was also destroyed. In many parts, the painting has been lost. In the '70s of the XX-th century, the damaged paintings were restored, and missing elements were reconstructed, but the character of the ancient painting was completely changed.

All over the surface of the dome, there are traces of past injections and anchors. Old putties were made of gypsum and cement. Some of them cover the original layers. XVIII-th century plasters had weakened adhesion to the support and poor cohesion. The surface of the painting was very dirty, and the colour of the old retouches was changed

3.1. Test site description –St. Anne’s Church

St Anne's Church in Warsaw, for several centuries a Bernardine church and now an academic building, is a significant and distinctive accent in the picturesque skyline of Warsaw. It is one of the oldest churches in Warsaw and one of the few churches with such a high percentage of authenticity, both in terms of the variety of style forms of the building itself, shaped during almost six centuries of its existence, and in terms of the interior furnishings. It is a Baroque temple (Figure 2b, d), and its location (Figure 2a, c) and history make it unique. It could be considered "a monument in constant damage". Due to that fact, St Anne’s Church requires time monitoring.

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(a) (b) (c) (d)

Figure 2. (a) Location of St. Anne's Church on a map of Warsaw; (b) The view of the Church from the west, (c) Digital Terrain Model of the slope with the marked Church; (d) The view of the Church from the west with marked Blessed Ladislas' chapel.

St. Anne’s church history is closely linked to the city's development as the prince's seat and then the kingdom's capital. Princess Anne of Masovia founded St. Anne's Church in Warsaw in 1453 for the Minor Order Friars brought from Cracow. A small gothic building was expanded in the XVI-th century by adding a huge nave. In the XVII-th century, the building was increased and obtained a new vault. In 1620 a Blessed Ladislas' chapel was added to the corps of the Church from its north side. The present mural decoration of the Church and chapel dates from the XVIII-th century. Between 1743 and 1750 one of the monks - Walenty Żebrowski accomplished a mural painting decoration in the church interior based on the extensive iconographic and religious program. The paintings in the chapel presenting the life of the Blessed Ladislas were created for a special occasion to announce his beatification. In the chapel's dome was placed a set of Polish Saints and Blessed, between which we can identify the artist himself and his co-worker's team composed of other monks.

4. Results

This chapter will present the results of the inventory and monitoring of the historic building and its immediate surroundings using, among other things, (1) classic surveying measurements, i.e. precision levelling and total station for the analysis of height and vertical displacements, (2) inclinometers for the measurement of the movement of the land around the Church and the escarpment, and (3) surveying measurements for the analysis of speckles and cracks.

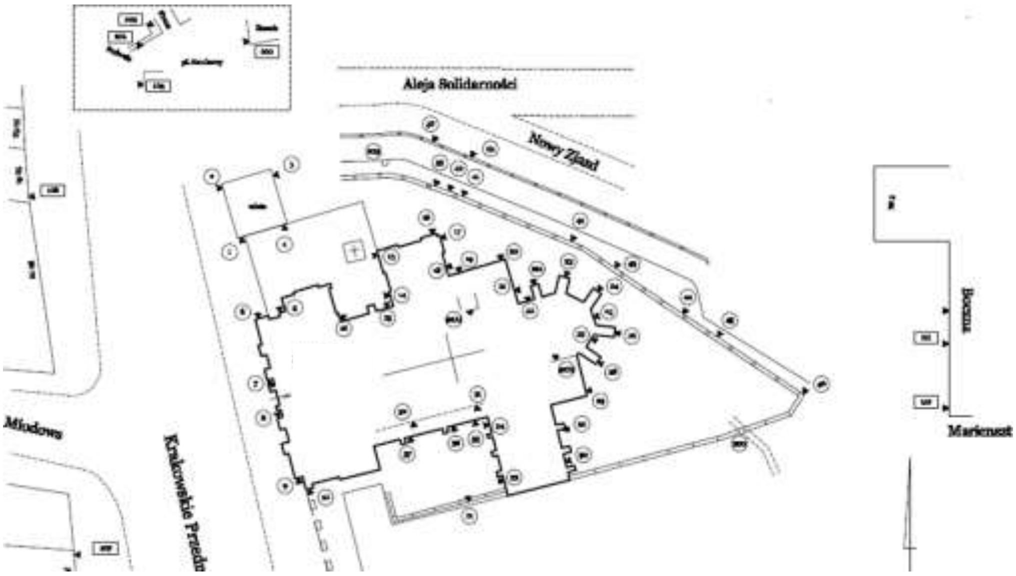
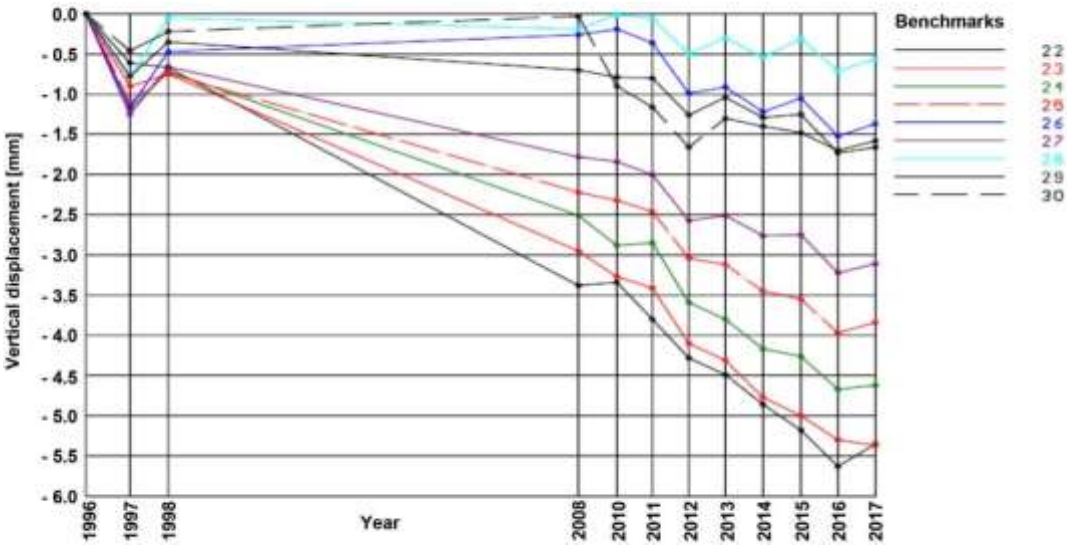


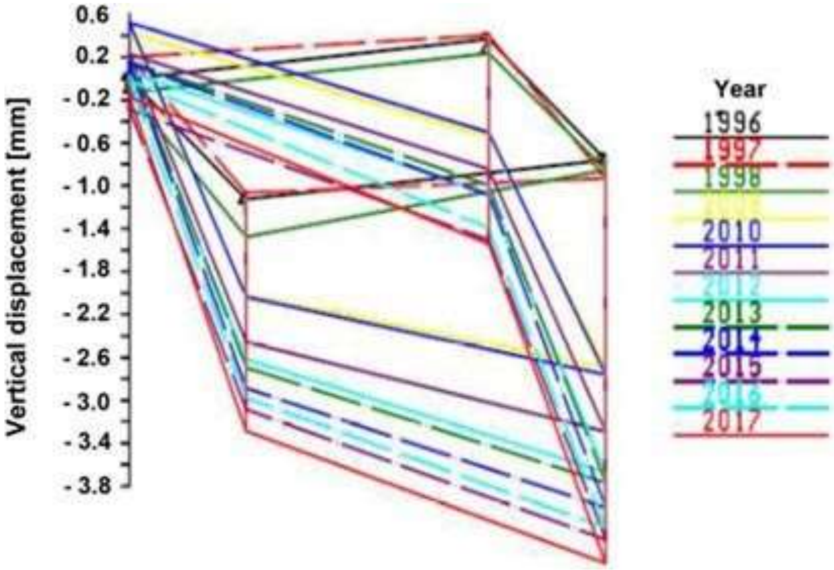
Figure 3. The sketch of the location of benchmarks for the determination of vertical displacements [44].

4.1. The vertical displacements monitoring

The first work to determine vertical displacement began in 1996, with measurements carried out using tacheometric technology. As part of the work, a first-order surveying network linked to the national reference system was established, which has since served as a reference frame. Therefore, the vertical displacements of the surveyed objects are determined regarding archival observations from the period 1996-1998. The control levelling measurements included a total of 12 reference benchmarks and 49 controlled benchmarks on the following objects: foundations and buttresses of the Church, the interior of the Church - a benchmark on the northern pillar by the rainbow arch and a benchmark on the southern wall by the main altar, tower, retaining wall, lower retaining wall. The location of the control and reference reps is shown schematically in Figure 3.



(**a**)



(**b**)

Figure 4. (a) Diagram of vertical displacement of the benchmarks on the tower side; (b) The diagram of the vertical displacement of the tower through the years [44].

The measurements were taken with a digital precision automatic leveller with a bar-code level rod. The processing of the measurement results included the following steps: (1) Pre-alignment of observations, (2) Identification of fixed reference points, and (3) Calculating vertical displacements based on the alignment of observed differences between the initial and current measurements. The study of the constancy of the reference benchmarks between the archival measurement and the current measurement was based on the analysis of the apparent displacements determined in the process of free alignment of observed differences. The final alignments of observation differences, aimed at calculating the displacements of the controlled benchmarks, were carried out using the indirect method with the adoption of a flexible reference system, with a base formed by reference points identified as fixed reference points. Examples of vertical displacement diagrams of selected benchmarks and the tower are shown in Figure 4.

4.2. The horizontal displacements monitoring

In order to determine the horizontal displacements of the Church, tower and retaining wall, reflective sights were set up on different levels and structures of the Church. The reference points (11-24), control points (1-7) and total station positions (101, 102 and 103) are shown in Figure 5. This figure also includes a sketch of the observations made. Measurements in the angle-line network were made with a Leica 1202 total station with angular accuracy of 6^{cc} and linear 0.5 mm.

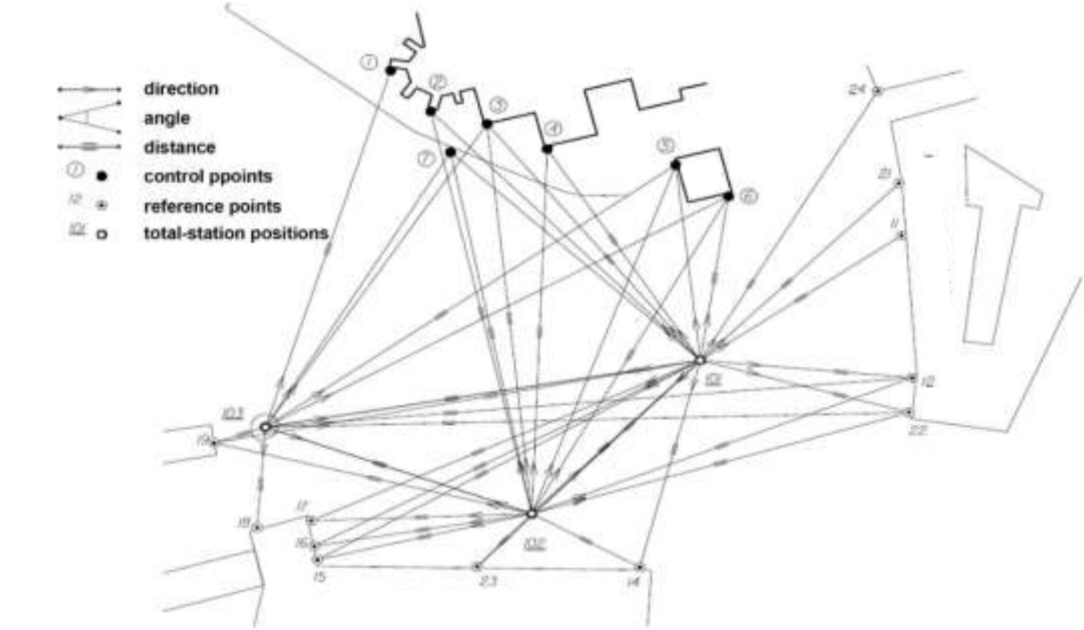


Figure 5. The sketch of an angle-linear network for horizontal displacement determination [44].

The values of the components of the horizontal displacement vectors were determined in the free alignment of the differences in observations between the 2010 year and 2017. Figure 3.1 shows the horizontal displacement vectors concerning the surveyed objects in annual cycles. Note the changing directions of the displacement vectors in the period 2014-2015-2016 - measurements in 2015 were made after a drought lasting several months. The 2017 measurement was taken after 2 months of rainfall. The horizontal displacements of the Church and tower in 2016-2017 are not outside the uncertainty range of their determination. The following is an evident Displacement trend of the retaining wall - total displacement since 2010 is 6.7 mm.

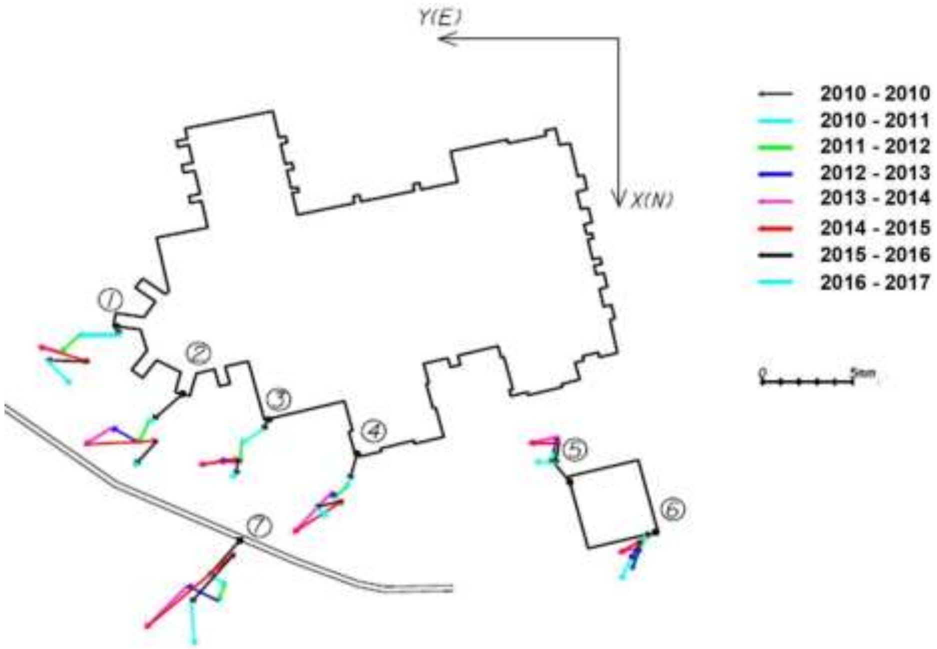


Figure 6. The sketch of horizontal displacement vectors (survey 2009-2017) [44].

To detect possible landslide movements in the slope of the hill of St Anne's Church, observations of inclinometers No. 1 and 2, located at a depth of 14 m, have continued since 2011, and since 2012 inclinometers No. 3 and 4, located at depths of 21 m and 25 m respectively (Figure 7). In 2017, measurements were taken on the 4th of April after a mild winter characterised by below-average precipitation/. The location of the inclinometric columns in the slope is shown in Figure 7. Examples of the results of inclinometric measurements in column 1, in the directions marked in Figure 7, are shown in Figure 8.

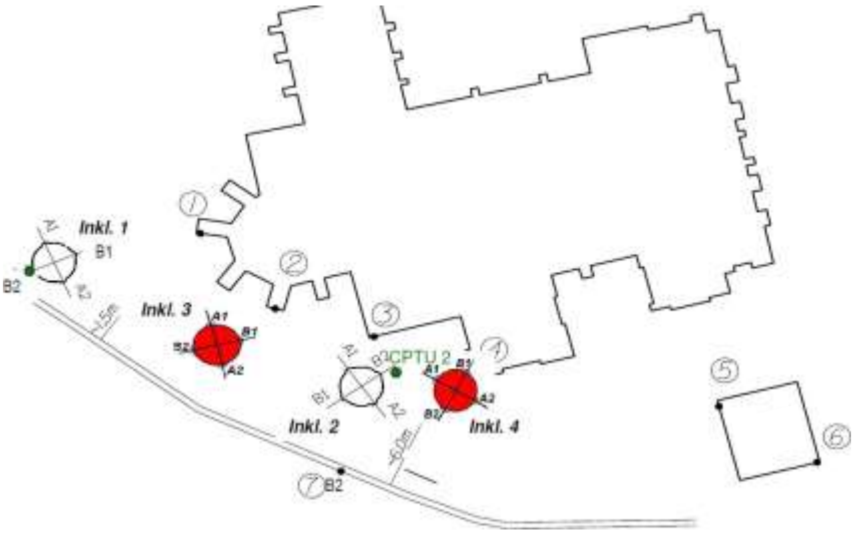


Figure 7. The sketch of inclinometer column arrangement [44]. Inclinometers 1 and 2 are seated at a depth of 14m, while inclinometers 3 and 4 are at depths of 21m and 25m, respectively.

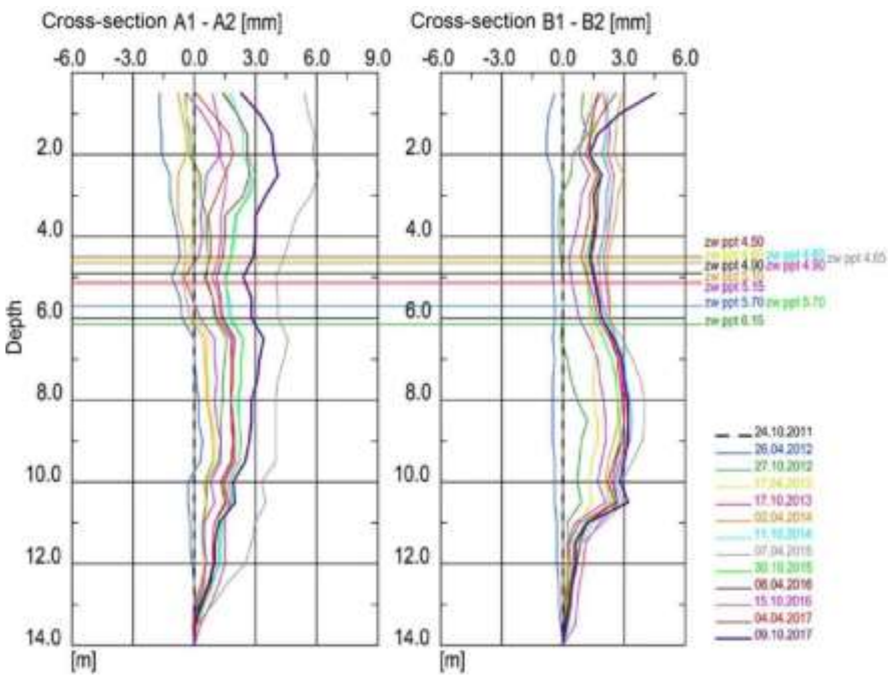


Figure 8. The inclinometer No. 1; horizontal displacement relative to slope base [44].

The analyses carried out show that the magnitudes of the absolute horizontal displacements of the inclinometer column heads not exceed the uncertainty range of their determination. However, they confirm the non-occurrence of significant displacements of inclinometric columns.

4.3. The crack monitoring

In order to analyse the size of the crack and determine the size of the cracks, it was decided to use direct measurements using crack gauges and measurements using a total station (Figure 9).

Figure 9. The example of the location of the measuring points in the nave (points 4 - 5) and of the bark gauges (points 3 and 9) [45].

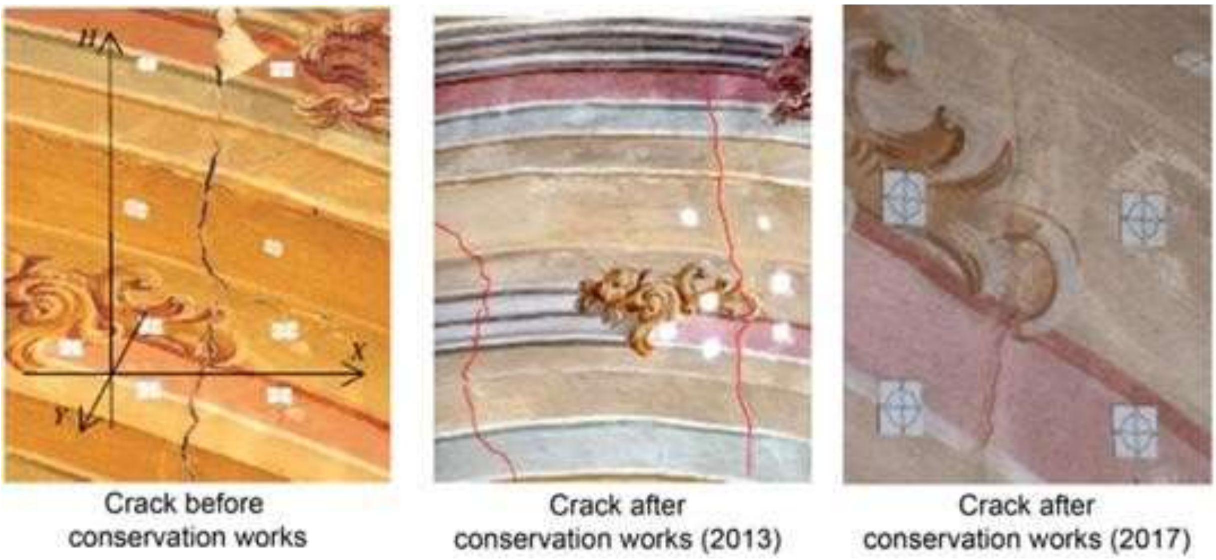


Figure 10. The example of the configuration of measurement points around a crack before and after conservation work [44].

Table 1. The example of crack width values before and after conservation work.

Date Temperature	ΔX [mm] / ΣΔX [mm]	ΔY [mm] / ΣΔY [mm]	ΔZ [mm] / ΣΔZ [mm]	$\sigma_{\Delta X}$ [mm]	$\sigma_{\Delta Y}$ [mm]	$\sigma_{\Delta Z}$ [mm]
Before conservation work						
	Displacement			**RMSE of displacement**		
30.09.2009 t = +12°C	0.0	0.0	0.0			
29.12.2009 t = -2°C	-0.1	-0.7	-0.1	0.3	0.3	0.2
28.01.2010 t = -6°C	+0.4 +0.3	-0.4 -1.1	0.0 -0.1	0.2	0.2	0.2
22.04.2010 t = +6°C	-0.6 -0.3	+0.2 -0.9	+0.5 +0.4	0.2	0.2	0.4
1.06.2010 t = +22°C	-0.2 -0.5	-0.1 -1.0	+0.2 +0.6	0.2	0.2	0.4
15.07.2010 t = +28°C	-0.4 -0.9	-0.2 -1.2	-0.3 +0.3	0.2	0.2	0.4
8.09.2010 t = +16°C	+0.1 -0.8	0.0 -1.2	-0.3 0.0	0.2	0.2	0.2
19.10.2010 t = +9°C	0.0 -0.8	+0.3 -0.9	+0.2 +0.2	0.2	0.2	0.2
8.12.2010 t = +1°C	+0.7 -0.1	-0.4 -1.3	+0.1 +0.3	0.1	0.1	0.2
28.02.2011 t = -5°C	-0.7 -0.8	+0.5 -0.8	-0.2 +0.1	0.1	0.1	0.2
5.05.2011 t = +7°C	-0.4 -1.2	-0.3 -1.1	0.0 +0.1	0.2	0.1	0.2
14.07.2011 t = +25°C	0.4 -0.8	0.0 -1.1	-0.1 0.0	0.2	0.2	0.2
10.10.2011 t = +18°C	0.0 -0.8	+0.5 -0.6	+0.2 +0.2	0.2	0.2	0.2
After conservation work						
18.04.2012 t = +10°C	0.0	0.0	0.0	0.2	0.2	0.1
17.04.2013 t = +18°C	0.0	0.0	0.0	0.1	0.2	0.1
16.07.2013 t = +24°C	0.0	0.0	0.0	0.1	0.1	0.1
15.10.2013 t = +14°C	0.0	0.0	0.0	0.1	0.1	0.1
2.04.2014 t = +12°C	-0.2 -0.2	0.0 0.0	-0.2 -0.2	0.1	0.2	0.2
20.10.2014 t = +15°C	0.0 -0.2	0.0 0.0	0.0 -0.2	0.1	0.2	0.2
17.04.2015 t = +5°C	0.0 -0.2	0.0 0.0	0.0 -0.2	0.1	0.2	0.2
27.10.2015 t = +12°C	0.4 0.2	-0.3 -0.3	-0.1 -0.3	0.1	0.2	0.3
1.04.2016 t = +10°C	-0.1 0.1	-0.2 -0.5	0.1 -0.2	0.1	0.1	0.3
19.10.2016 t = +10°C	-0.4 -0.3	+0.3 +0.2	0.0 -0.2	0.1	0.2	0.2
4.04.2017 t = +13°C	+0.4 +0.1	-0.5 +0.3	+0.1 -0.1	0.1	0.2	0.2
5.10.2017 t = +12°C	-0.1 0.0	+0.1 -0.2	0.0 -0.1	0.1	0.2	0.2

Changes in the width of fractures not available for direct measurement were determined by observing retroreflection points stuck in the fracture region. The observations were made from free-standing positions, and the final values of relative displacements in the region of the controlled crack were obtained by local transformations (using the Helmert method) of the x,y,h coordinates of the observed points. Examples of the location of the measurement points in the area of the investigated cracks are shown in Figure 10. The table 1 summarises the values of the relative displacements in 3 directions: X (north), Y (east) and H (height).

5. Summary

From the analysis of the multi-temporal data, it is apparent that there are uneven settlements of the repertory in individual fragments of the body of the Church, chapels and adjacent buildings. Since August 2009, i.e. since the resumption of observations of the Academic Church of St. Anne's, the vertical displacements of individual fragments of the surveyed object are significant, i.e:

- from -2.6 mm to -1.4 mm in Loretto Chapel (benchmark no.15-18),
- from -3.1 mm to -2.3 mm in St.Ladislaus Chapel (benchmark no.19-21),
- from -2.3 mm to -2.0 mm in the buttresses of the apse on the side of Trasa W-Z (benchmark no. 22-24),
- from – 1.5 mm to – 0.3 mm in the buttresses of the apse on the east side (benchmark no. 252-28),
- from – 1.8 mm to – 1.0 mm in the presbytery (benchmark no. 52-south side and benchmark no. 51-south side),
- from – 2.1 mm to + 0.4 mm in the tower (benchmark no. 1-4), tilt of 1.3mm towards the W-Z Route exit over a period of 8 years,
- from – 1.7 mm to + 2.2 mm in the upper retaining wall (benchmark no. 39-46), uplifts occur in the upper part of the slope and in the lower corner,
- from – 3.0 mm to + 2.6 mm in the lower retaining wall (benchmark no. 55, 56), monitored from 2010r.

The magnitudes of relative and 'absolute' displacements (relative to reference points located outside the Church) are well beyond the range of uncertainty of the surveying measurements. They, therefore, provide authoritative information about the behaviour of the body of the Church, the Tower and the Retaining Walls. Particular attention should be paid to the uplift of the benchmarks in the lower and upper retaining walls, with simultaneous subsidence of the chapels on the side of the WZ Route and the apse.

The vectors of horizontal displacements, determined since February 2010, correspond to thermal changes and the intensity of precipitation during the analysed study periods. Note the changing directions of vectors of displacements in the period 2014-2015-2016. The return trend visible in the period 2014-2015 may reflect the impact of a prolonged drought - in 2015 on the condition of the slope. The length of the Church's horizontal displacement vector since 2010 reaches 4mm, and the displacement of the retaining wall - in the central cracked section – reaches 6.7mm.

A summary of the observations of inclinometers 1, 2 and 3 indicates a northeastward displacement trend of the soil slightly exceeding the uncertainty range of its determination. The cumulative relative horizontal displacements in column 4, periodically exceeding the uncertainty interval of their determination, may be due to measurement errors caused by a twisting of the shape of this column.

Observations of changes in the width of cracks on the walls and vault of the nave, apse and the chapel of St Ladislaus indicate the instability of the body of the Church. Measurements of the bolt crack gauges, set up in the vault of the nave on the side of the attic, have been carried out since 14 March 2014. The effects of temperature on crack opening. The most significant changes are found in the north side's central part of the vault.

The monitoring (completed in 2017) and Structural Health Monitoring results influenced the decision to start restoration work in St Anne's Church. For more on this topic, see the article by Markiewicz et al. , entitled The Integration Of The Multi-Temporal Conservation Works And Non-Invasive Measurements [46].

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