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Review article

RESEARCH AND DEVELOPMENT WORK CARRIED OUT BY THE CHAIR OF ENGINEERING GEODESY AND MEASUREMENT AND CONTROL SYSTEMS, FACULTY OF GEODESY AND CARTOGRAPHY WUT – THEMATIC SCOPE AND ACHIEVEMENTS

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Abstract

Geodetic engineering surveys are an important part of the works carried out by the Faculty of Geodesy and Cartography, Warsaw University of Technology. These works concern measurement techniques as well as advanced result analysis methods applied in precise industrial surveys and in processes controlling object's behaviour over time.
The thematic scope of research realised by Chair of Engineering Geodesy and Control-Measuring Systems shows that article related to geodetic engineering measurements and geodetic monitoring is carried out with high intensity, resulting in technological advancement and implementation of new or improved measurement solutions and methods of measurement result development.

Keywords: *Engineering Geodesy, Chair of Engineering Geodesy and Control-Measuring Systems, scientific research*

1. Introduction

Geodetic engineering surveys are an important part of the works carried out by the Faculty of Geodesy and Cartography, Warsaw University of Technology. These works concern measurement techniques as well as advanced result analysis methods applied in precise industrial surveys and in processes controlling object's behaviour over time.

Geodetic monitoring of shifts of engineering objects is the topic of profound scientific research carried out by the Chair of Engineering Geodesy and Control-Measuring Systems (Chair of GIiSPK, previously: Department of Engineering and

Industrial Geodesy). Prof. dr hab. inż. Tadeusz Lazzarini was the founding father of studies in this field.

Application of new measurement techniques and new methodological solutions of identifying shifts is realised for the needs of various engineering objects.

The following themes may be counted among the main fields of research for the Chair:

- improvement of geodetic precise engineering measurement techniques,
- design of systems monitoring shifts in engineering objects and identifying deformation parameters,
- improvement of methods concerning accuracy analysis for specific geodetic engineering measurement tasks as well as development of reliability theory and gross error detection methods in monitoring systems,
- methodology of automated measurement and construction of control systems as well as creation of local geographic information systems,
- recognition of geodetic, geophysical, satellite observations and digital imaging in the process of identifying geometry and determining shape changes of artificial and natural objects,
- assistance in managing constructions characterised by complex geometry and high accuracy requirements
- monitoring of shifts in high risk engineering objects, i. a. in hydrotechnical objects such as Rybnik, Żarnowiec, Żar, Wióry, Włocławek, Rożnów, Klimówka, Besko , Solina reservoirs and selected engineering objects in Bełchatów Power Plant (chimneys, cooling towers, carbonization galleries)
- establishment of vast multifunction geodetic networks, i. a. for Legnica-Głogów Copper Belt (LGOM), Lublin Coal Basin and of control networks for „Zbiornik Lubin" and „Żelazny Most" tailing ponds,
- supervision over geodetic works during various construction phases of Warsaw Metro. The scope of the works comprised establishment of master surveying grid, disc guidance, assistance in computing tasks concerning setting out works and design of shift identifying systems. In order to control the state of the encountered hazards for the site's surroundings in the deep building pits a concept of automated shift monitoring system was designed.
- supervision over geodetic works connected to the construction of bridges in Warsaw, i. a. Świętokrzyski and Siekierkowski bridges as well as design of monitoring systems for those objects,
- monitoring of shifts and deformations of heritage buildings: the Grand Theatre and Opera complex, the Royal Łazienki park complex, Academic Church of St. Anne, Ostrowski Palace and Lubomirski Palace.

The research tasks are consistent with development directions for the scientific discipline of Geodetic Engineering observed worldwide. Special emphasis is put on construction of automated shift and deformation monitoring systems that base on the information obtained utilising geodetic and non-geodetic techniques. The issues concerning reliability analyses of observation systems, diagnostic methods and algorithms also comprise an important field of research for the Chair.

2. Monitoring shifts and deformations in engineering constructions and hydrotechnical objects

Towards the end of the 1940s a number of research works aiming to identify shifts of water dams and heritage and industrial objects was carried out by the Chair of Precise Geodetic Measurements under the guidance of prof. Tadeusz Lazzarini.

In contrast to the commonly used, at that time, solutions which utilized transformation of the coordinates, a new method to identify shifts was developed that exploited result differences of the periodic measurements in the process of identification of reference points and shift determination in various types of networks (full trigonometric networks, linear networks, linear and angular networks as well as levelling networks). The innovative achievement of prof. dr hab. inż. Tadeusz Lazzarini, prof. dr hab. inż. Andrzej Hermanowski and dr inż. Irmina Laudyn contributed to the creation of the methodological basis for the differencing method, which was appointed as the leading technology for determining shifts and deformations in various types of objects and engineering constructions. As a result of the research carried out on the largest hydrotechnical objects in Polad i. a. Rożnów (fig. 1), Czchów, Solina, detailed instructions and recommendations concerning measurement technology and absolute horizontal and vertical shift calculations were formed.

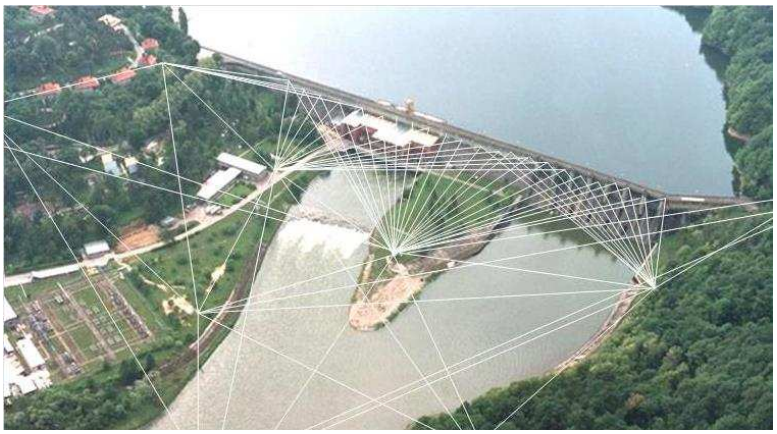


Fig.1. Rożnów dam on the Dunajec river with inscribed trigonometric network, geometry affixed for horizontal shift study

Later, a distinctive solution that involved the design and realisation of monitoring observations for objects that were unstable over one measurement cycle was developed basing on the experiences of the employees of the Chair. It was the first step towards integration of various measurement techniques in order to control hydrotechnical objects. Upper reservoir of the Żarnowiec Hydroelectric Power Plant was one of such objects. The research work carried out in the years 1999-2006 allowed for establishment of a complex measurement and shift identification technology for this type of objects (Woźniak et. al., 2003). Many of the research studies on this object were directed by dr hab. inż. Marek Woźniak, prof. PW.

Monitoring was carried out using the so-called hybrid network combining classic observations with GPS observations and original research of short-term changes done in order to control geometry changes of the upper reservoir's crown (fig. 2).

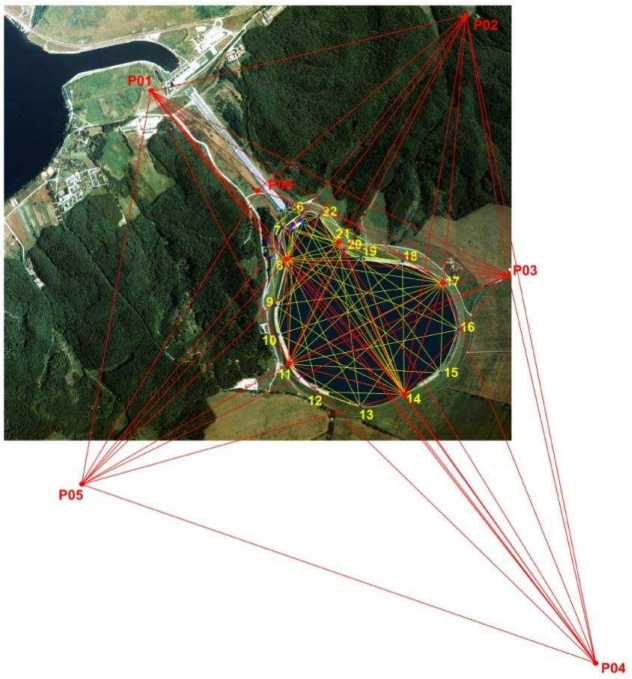


Fig. 2. Żarnowiec hybrid control network

This task called for precise observations that would allow for acquisition of absolute coordinate values for a vast object with strong influence over extensive part of its surroundings. The suggested solution met all the expectations as far as identification of shift vectors was concerned. During the realization of the measurements considerable changes in object's geometry were observed while it performed its basic tasks (filling and emptying of the reservoir). In order to carry out the observations under operating conditions it was essential to determine reservoir's behaviour in a day-night cycle. Synchronous linear observations provided an image of the reservoir's crown represented by 23 points controlled in a 30 minute cycle (fig. 3).

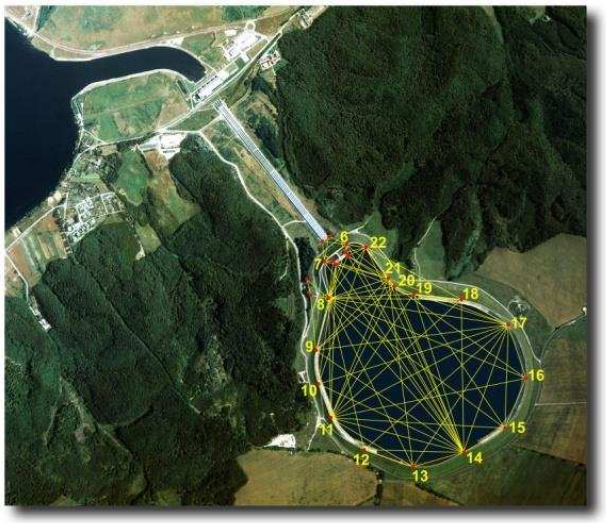


Fig. 3. A diagram of the control network used for short-term change research on the ESP Żarnowiec's upper reservoir.

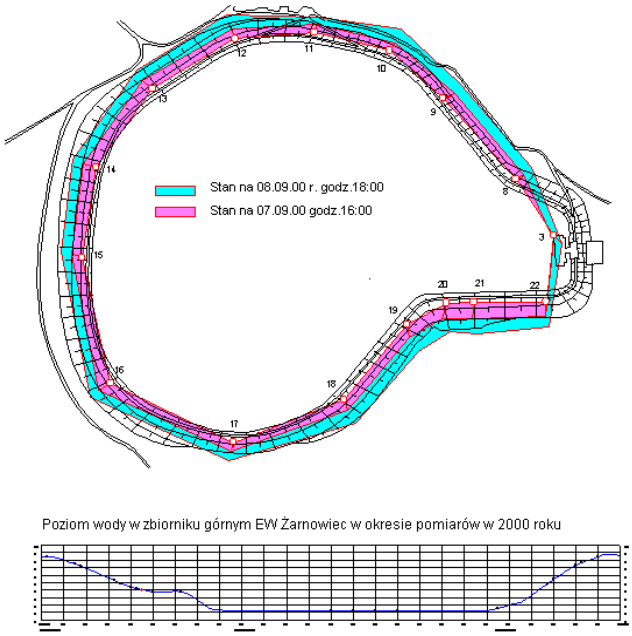


Fig. 4. Deformation of the crown of the ESP Żarnowiec's upper reservoir.

Study of the short-term changes of the reservoir's crown provided new, reliable data for the hydrotechnicians on the reservoir's reaction (fig. 4) that may serve as a basis when designing new objects of this type.

In this type of studies, apart from identifying the shift of reservoir's crown, it is crucial to determine the delay in the reservoir's reaction to the changes in water level and as a result changes in structural load (fig. 5). It is a particularly important element that has to be take into consideration when designing hydroelectric power plant's reservoirs, creating prognoses and monitoring changes of their shape.

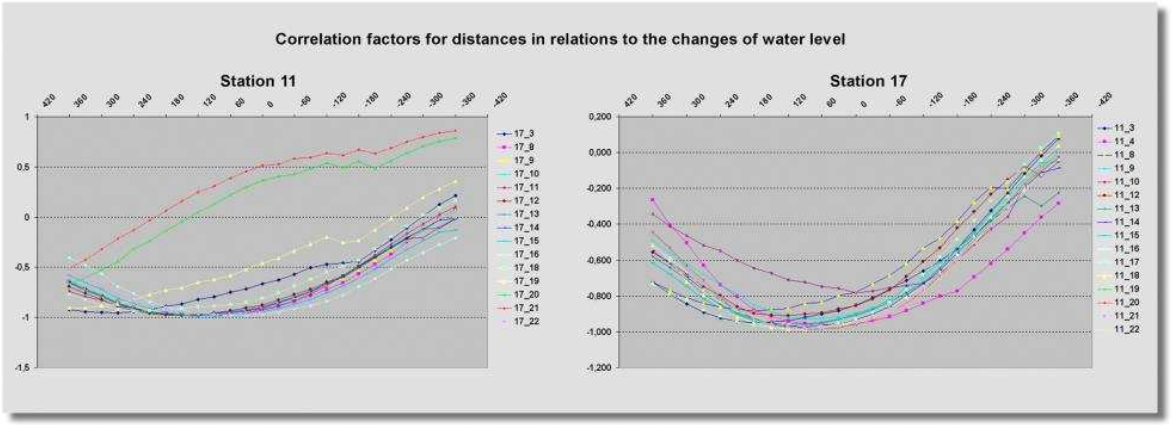


Fig 5. Changes in correlation coefficient value between object's load and its geometric reaction

Methodology related to design of control networks is an important aspect of the studies aiming to investigate any object's behaviour. In the case of hydrotechnical objects, the precision indexes referring to the identified shifts are most often taken into consideration. For many objects the control networks were designed a long time ago. In the case of the oldest objects in Poland they were created at the turn of the 19th and 20th centuries. Addition of measurement points, enabling utilization of

modern measurement techniques and the increase in reliability of the control network is a vital step towards modernization of the said networks. Angular and linear control networks (designed as full trigonometric networks) used to study horizontal shifts of Besko and Zatonie dams can be counted among those. They were originally designed as full trigonometric networks. A detailed project concerning supplementation and redevelopment of the control network in Besko dam accompanied by introduction of GNSS control techniques and telemetry was designed within the framework of the PhD thesis titled "The concept of modernization of classic horizontal networks used to identify shifts of hydrotechnical objects" (Zaczek-Peplinska, 2007a), (Zaczek-Peplinska, 2007b).

Zatonie dam control network was also the subject of analyses. The first of the analyses covered the issue of reference point stability over the period of 20 years (Odziemczyk, 2014). The same control network was used as a basis to form a methodology for the reconstruction of water dam control networks aiming to increase their reliability. A team supervised/guided by Prof. dr hab. inż. Edward Nowak as part of the carried out analyses considered adding of free stations that would not comprise the potential reference framework. The analyses were performed using numerical simulation method. Existing data from the previous surveys and proprietary software was used for computing purposes. This type of analysis was referred to as "measurement network reliability reconstruction".

3. Development of the basis of observation system reliability theory and its application in geodetic engineering measurements

In the topic of reliability theory, the research was carried out from a general point of view that is in reference to stochastic linear models (Gauss-Markov Models – GMM) with parameters estimated using least squares method. Detailed research was undertaken on measurement and control networks used in geodetic engineering measurements comprising observation system characterised by low level of redundancy (that is surplus of observations).

General research was focused mainly on:

- properties of orthogonal projection and oblique view operators relating to linear model reliability mechanism (Prószyński, 1994, 1997, 2010),
- measures of internal reliability and relating thereto reliability criteria for systems with uncorrelated and correlated observations (occurrence of a single gross error or a number of gross errors) (Prószyński, 1994, 1997, 2010, 2012, 2014, 2015),
- rules of gross error propagation in measurement construction characterized by a specific structure (Prószyński, 2000),
- reliability specifics of systems characterized by low level of redundancy (unnoticeable error space, unidentifiable error regions) (Prószyński, 2008), (Kwaśniak, 2009),
- grounds for classification of gross errors (Prószyński, 2008),
- use of durability analogy in forming measures for network's internal reliability (Gambin et al., 2008), (Szostak-Chrzanowski, et al., 2006),
- theoretical grounds for designing measurement constructions with uncorrelated observation as well as constructions with correlated observations (Nowak, 2011), (Nowak, Prószyński 2012).

Detailed research focused on, i. a. :

- seeking dependencies between diagnostic effectiveness of parameter estimation and reliability properties of the examined observation systems (Kwaśniak 2012). Selected methods of robust estimation were also researched (Kwaśniak 2011a, 2011b),
- research and improvement of methodology concerning automated reliability development of measurement constructions, with a particular focus on the needs of geodetic engineering measurements (Nowak 2012).

What is more, a number of studies ending with a publication was carried out in regard to defining reference systems and methods of identifying reference systems in control networks for static and kinetic models (Kwaśniak 2015, Prószyński 2003, 2010), methods of tying measurement networks (including non-destructive tying), parameter vector transformation (for position and position changes) and its covariance matrix for transition from one internal system to another one and from an internal system to an external one and vice-versa (Prószyński 1986), matrix solutions for linear system minimizing pseudonorm of unknown vector and pseudonorm of residue vector (Prószyński, Sosnowski 1995), dependencies between observation orders of coexistence and correlation matrix of those observations after offsetting (Kwaśniak 2008).

4. Evaluation of the condition of hydrotechnical objects based on the results of terrestrial laser scanning

Since 2009 a team employed by Chair of Engineering Geodesy and Control-Measuring Systems directed by dr inż. Janina Zaczek-Peplinska has been developing a methodology for the purposes of inventory surveying of solid hydrotechnical objects with the application of terrestrial laser scanning method. Measurements of water dams in Besko (fig. 6,7), Solina, Rożnów, Klimkówka, Eckertalsperre were carried out as part of experimental and professional surveys. The team collaborates with Leica Geosystems Polska, Laser-3D, utilising Leica ScanStation 2, Leica C10, Riegl VZ-400, Z+F Imager 5010 scanners with various technical parameters. The work of the team results both in numerous publications in national journals and presentations at conferences worldwide. The members of the team are also authors and co-authors of chapters published in sectoral publications of Institute of Meteorology and Water Management (Zaczek-Peplinska et al., 2011, 2013a, 2013b, 2015a, 2015b).

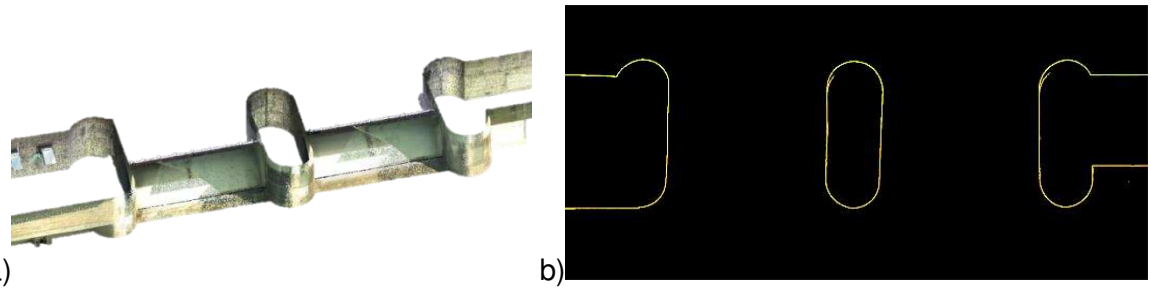
In 2011, cooperation with Remote Sensing and Spatial Information Systems team, Faculty of Geodesy and Cartography, Warsaw University of Technology was established with aim to utilise the data obtained using laser scanners in order to assess the technical condition of surfaces belonging to engineering objects. Research is being conducted on the application of multisource data, including registered reflected laser beam's intensity value and thermal imaging. in their tasks) The team utilises modern scanners with integrated thermovision cameras (Z+F Imager 5010C scanner with T-Cam thermovision camera) (Zaczek-Peplinska et al., 2012).

The project covers an important subject matter which is analysis of various factors influencing the "I" value. The analysed factors include: influence of the light beam's angle of incidence, physical properties of the material, colour of the surveyed

surface, distance, external lighting, influence of humidity on the surface, surface temperature etc. These factors were previously described by other researchers ex. (Boehler et al., 2004), (Koska et al., 2004), (Voegtle et al., 2008), (Voegtle et al., 2009), but it is essential to carry out appropriate experiments for surfaces made of solid hydrotechnical concrete.

The research conducted by the team aims to create non-destructive method of evaluating the condition of surfaces belonging to large hydrotechnical objects. The developed algorithms evaluating the condition of concrete surfaces on the basis of laser scanning results will be applicable also in studying concrete objects other than water dams e.g. elements of the bridges, bridge pylons, solid columns and beams like, for example, solid construction of the Temple of Divine Providence in Warsaw.

Fig. 6. View of clouds tinged using digital images as reference.



a) b)

Fig. 7. Results of Besko dam survey: a) model of the exterior surface of the dam, b) horizontal section of the object (above the spillway below the bridge plate in the dam's crown point).

5. Inventory and deformation monitoring in deep excavation regions using various measurement techniques

Dynamic development of the construction industry in areas of urban agglomerations and construction of underground objects poses a direct and indirect threat to the surrounding objects (Woźniak, 1999), (Prószyński, 1999). The occurring problems manifest themselves in the form of many construction disasters that result from the construction works being carried out in the immediate vicinity of existing objects or even below them, as is the case with tunnels.

EUROPLEX construction disaster in Warsaw was the first object to be subjected to a very detailed and comprehensive monitoring measurements involving all measuring techniques starting from precision levelling, through angular and linear

measurements, GPS observations to photogrammetry. Neighbouring buildings, ground base and pavements around the object, diaphragm walls, supporting components and the elements of the constructed building were controlled. This served as a test field in the field of geodesy and inventory monitoring. The work was directed by prof. dr hab. inż. Witold Prószyński and dr hab. inż. Marek Woźniak, prof. PW.

Shift monitoring carried out in the form of a planned monitoring for the BLUE CITY object (fig. 8) shared some similarities. As in the previous case, precise geodetic measurements were applied using classic observation techniques and GPS.

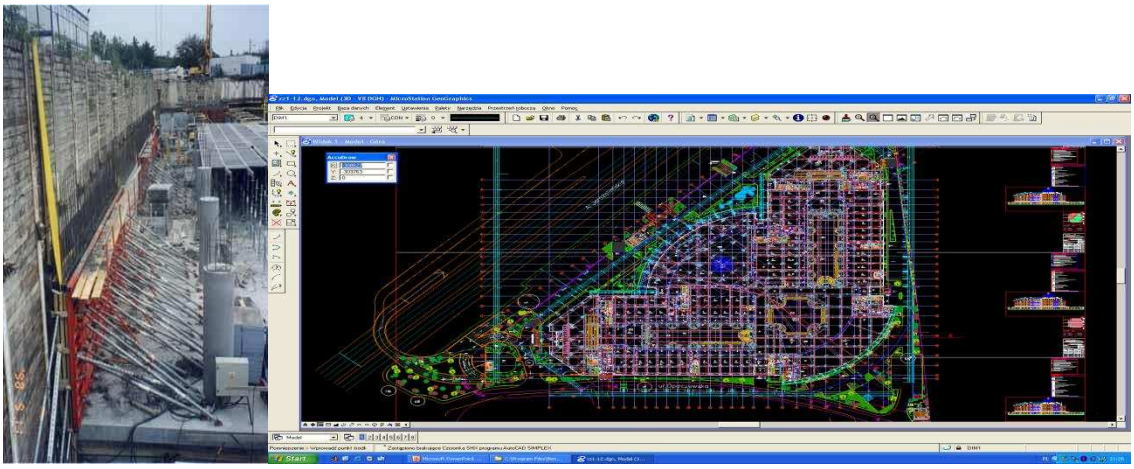


Fig. 8. Anchored Berliner wall and view of supporting components for 3 storey deep underground part of the object.

Terrestrial laser scanning can supplement classic methods by providing satisfactory accuracy (Zaczek-Peplinska et al., 2013c, 2013d; Woźniak et al, 2014). The basic products obtained through terrestrial laser scanning study are three-dimensional models of the scanned objects in the form of point clouds. The cloud also provides precise information on the object's geometry. Owing to the realisable high resolution it delivers quasi-continuous information on the scanned object without the necessity to signal measurement points (Zaczek-Peplinska et al., 2013, 2014).

Detailed consideration concerning analysis of the data from scanning were carried out by a team directed by Prof. dr hab. inż. Edward Nowak (Nowak et. al., 2003). It is possible to generate appropriate cross sections and to carry out secondary measurements of the interesting elements from the registered point clouds. Moreover, hypsometric maps can be generated from the point cloud that represent object's geometry in regard to a defined plane. They are usually prepared in regard to the targeted vertical plane. Such map makes it possible to assess the deviation of the studied surface from the plane. What is more, basing on the data from scanning, various analyses and spatial transformations cam be performed (Woźniak et al., 2014).

Terrestrial laser scanning is excellently suited for creating inventories of geometric and physical characteristics of diaphragm walls as well as other construction objects. It allows for acquisition of graphical studies that provide not only information on the object's geometry, but also on its physical characteristics like surface dampness, texture or the used type of material (Zaczek-Peplinska J., el. al. 2014).

6. Shift and deformation measurements of historical objects

Among historical objects monitored under the supervision of the employees of the Chair of Engineering Geodesy and Control-Measuring Systems, Academic Church of St. Anne deserves particular attention. The church, located on the Vistula escarpment exhibiting pronounced landslide tendencies, is one of the oldest churches in Warsaw.

In autumn 1948, during earth mass disposal while constructing Trasa W-Z, the tall escarpment on which the church is located begun to sink, causing church's vaulted ceilings to fissure and the sanctuary and the chapel to slide.

In April 1949 prof. dr hab. inż. Tadeusz Lazzarini was appointed to Emergency Council aiming to contain the landslide on the St. Anne Church hill. Horizontal shifts of the church's edifice itself and its surroundings were determined using trigonometric measurements (fig. 9) and vertical shifts were identified using precise levelling metod (fig. 10).

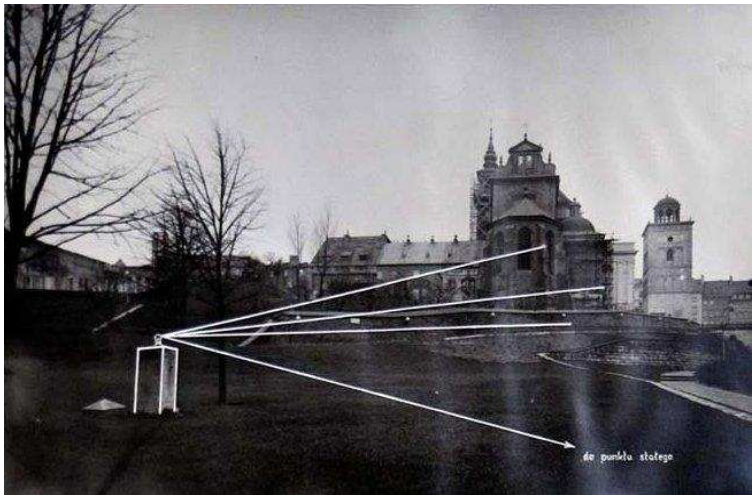


Fig. 9. Diagram presenting observation scheme to the selected control points (1949 r.)

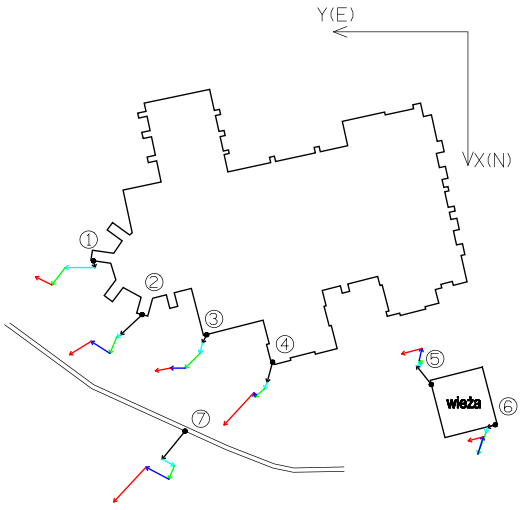


Fig. 10. Study presenting vectors of horizontal shifts (survey 2009-2015)

At present, the Chair of Engineering Geodesy and Control-Measuring Systems monitors shifts and deformations of control points in St. Anne Church area. A team directed by dr inż. Ryszard Malarski performs the following geodetic tasks:

- determining vertical shifts using precise benchmark levelling measurement method. The benchmarks are located on the church, retaining walls and the belfry,
- determining horizontal shifts using spatial measurement method,
- determining changes in the width of the fractures on church's walls and vaulted ceilings,
- determining relative horizontal shifts of the escarpment basing on inclinometric observations.

The results of geodetic surveys are essential for the stability assessment of Academic Church and key to taking appropriate preventive and repair measures (Malarski et. al., 2012, 2013a, 2013b).

7. Geodetic scientific supervision over construction and exploitation of Warsaw Metro

The construction of the I Metro line was a technical challenge for underground civil engineers and geodetic engineers alike. From the very start employees of Department of Geodesy and Cartography took active part in tasks concerning realisation of this underground construction. Prof. dr hab. inż. Tadeusz Lazzarini was the first of them. He organised a team of specialists providing substantive support for geodetic services required by the project. The tasks related in particular to tying of horizontal and vertical control networks, development of measurement technologies that ensured high reliability and accuracy of undertaken geodetic tasks while drilling tunnels, construction of train infrastructure, development of computing systems supporting the tasks in phases of project design, setting out and shift monitoring. Those works were frequently ahead of their time on the scale of our country.

From 1986 to the present date dr hab. inż. Marek Woźniak, prof. PW takes part in scientific supervision over construction of Warsaw Metro. A number of new solutions and studies supporting geodetic tasks were formulated over the years dedicated to realisation of projects concerning Metro construction, including:

- software designed to perform multifaceted analyses and alignment of angular, linear and levelling networks,
- software for object and construction geometry analyses and route variantation in 3D space,
- graphic systems used to create complex graphical and analytical studies and maintain maps in numerical form (fig. 11),
- systemic solution to shift monitoring of metro objects and the surrounding area during construction phase and establishment of levelling network for vertical shift monitoring purposes,
- carrying out scientific supervision over measurement techniques used to measure geometry of the tunnel and its infrastructure as well as study and result presentation methods.

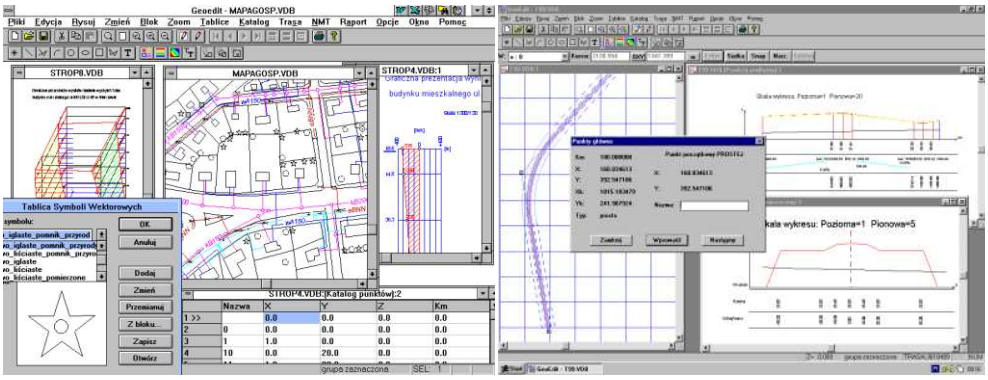


Fig.11. Selected computer software providing support for surveying services of the construction tasks

Those action are crucial to provide professional and safe completion of the metro construction carried out in difficult condition of dense urban areas characterised by significantly diverse geotechnical properties. The developed system is fit to be utilised in other underground construction projects as well as for construction of rail and road routes.

8. An example of implementation of new technological solutions in deformation measurements and skylight construction in PW's (Warsaw University of Technology) auditorium.

Due to extreme conditions in the skylight area, continuous monitoring of its construction's behaviour is only possible using remote control systems for geodetic instruments. In this case measurement was aided by TC-calc system developed by Waldemar Odziemczyk and Marek Woźniak. Owing to that solution a multi-day geometry change measurement carried out in conditions of very high temperatures reaching 58ºC was performed from the staff rooms (Woźniak, 2005; Woźniak et al., 2009).

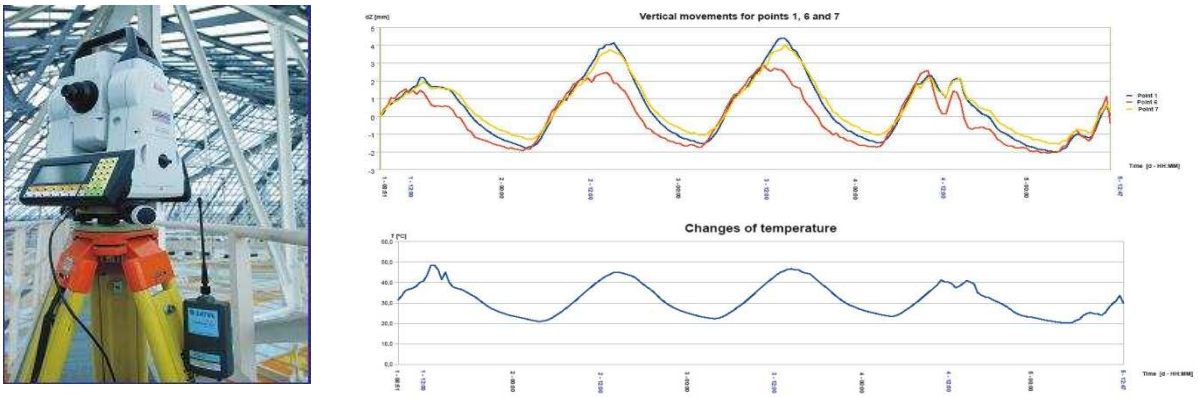


Fig. 12. Measurement station and the results of daily geometry changes and the occurring time correlations.

Innovative solution of determining structure deflections of the skylight's construction was realised through digital image registration using digital image

comparison algorithms with application of cross correlation and mutual information methods.

With this method, it is possible to determine the scope of relative shifts of the construction using areas of raster image without the necessity to signal measurement points beforehand. This approach is well suited for global evaluation of local deformation sizes in situations when there is no possibility to stabilise control points in the traditional way. Conceptual solution to this problem was authored by Krzysztof Woźniak (Woźniak K., 2009). Experimental measurements and development of applicable software in the form of an application for MatLab system was realised by the Chair as part of statutory research.

9. Study on deformation of cooling tower's sheath using videotachymetric technique

Measurement and deformation identification for sheath of the cooling tower in Bełchatów was realised using original surveying grid solutions and videotachymetric measurements. The grid for project realisation purposes consisted of reference points for measurements using Image Station IS03 video-tachymeter manufactured by Topcon, while all measuring positions were not fixed (fig.13).

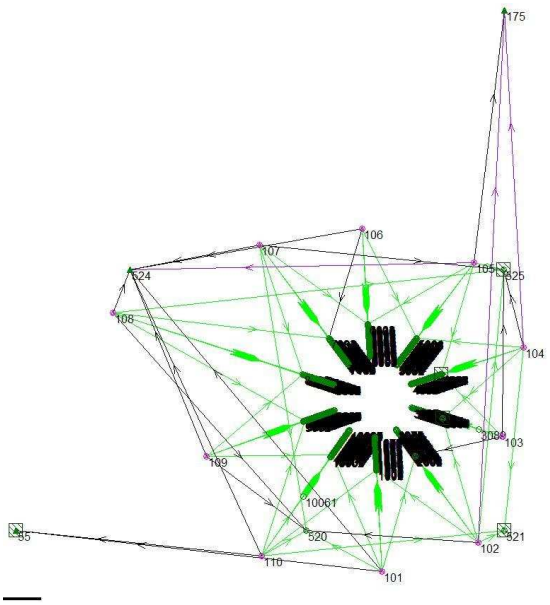


Fig. 13. Observation scheme of the control network

Geometry measurement of the sheath was carried out using two methods: profiling method and tachymetric scanning method supplemented by photographs taken using a digital camera integrated with the instrument (Woźniak M., Woźniak K., 2011a), (Woźniak M., Woźniak K., 2011b).

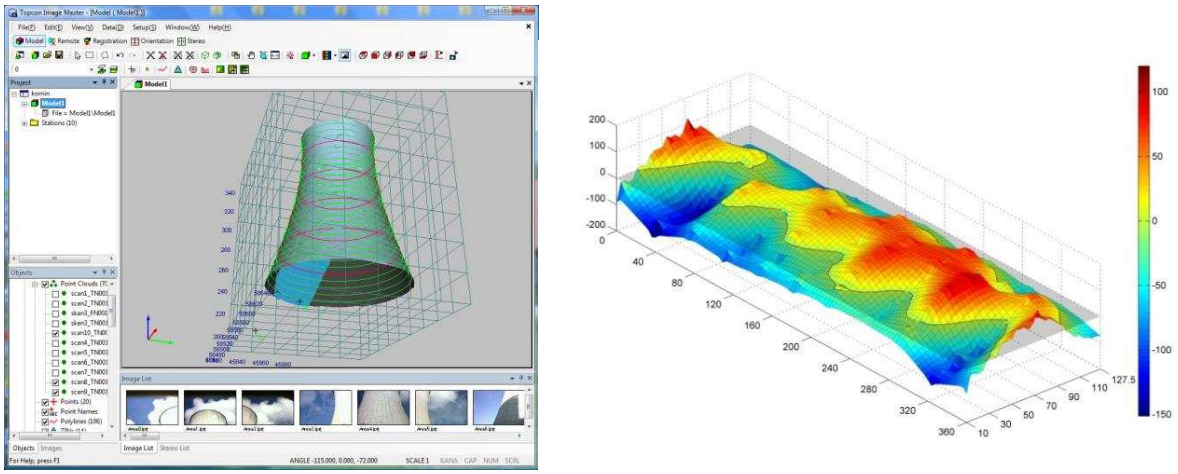


Fig. 14. Different stages of data processing concerning measurements of the cooling tower using videotachymetric technique.

The developed measurement technology combines both the original surveying grid solution and technology of running the measurement with automated analysis of geometric shape of the sheath and comparison to its nominal state (fig. 14). This method is a quick and reliable way to resolve tasks related to studying shapes of enveloping objects (cold storages, reservoirs, chimneys etc.).

10. Geodetic supervision over bridge construction

Construction of bridges requires many stages of geodetic work, starting from supplying maps for design purposes, through tying of special surveying networks and realisation of requested tasks, work during proofing load to measurements monitoring object's behaviour during operation.

During the bridges construction works employees of the Chair were actively involved in tying of the vertical and horizontal control networks for those objects and supervised geodetic work during all phases of construction. The work was directed by Prof. dr hab. inż. Witold Prószyński who closely collaborated with the designer and the site management team. The complexity of the bridge construction is illustrated in fig. 15.

Geodetic services provided during bride construction require vast experience in the field of concrete structure response and development of appropriate technology for setting out purposes in consecutive stages of construction. In these cases close collaboration between geodesists and builders is essential.

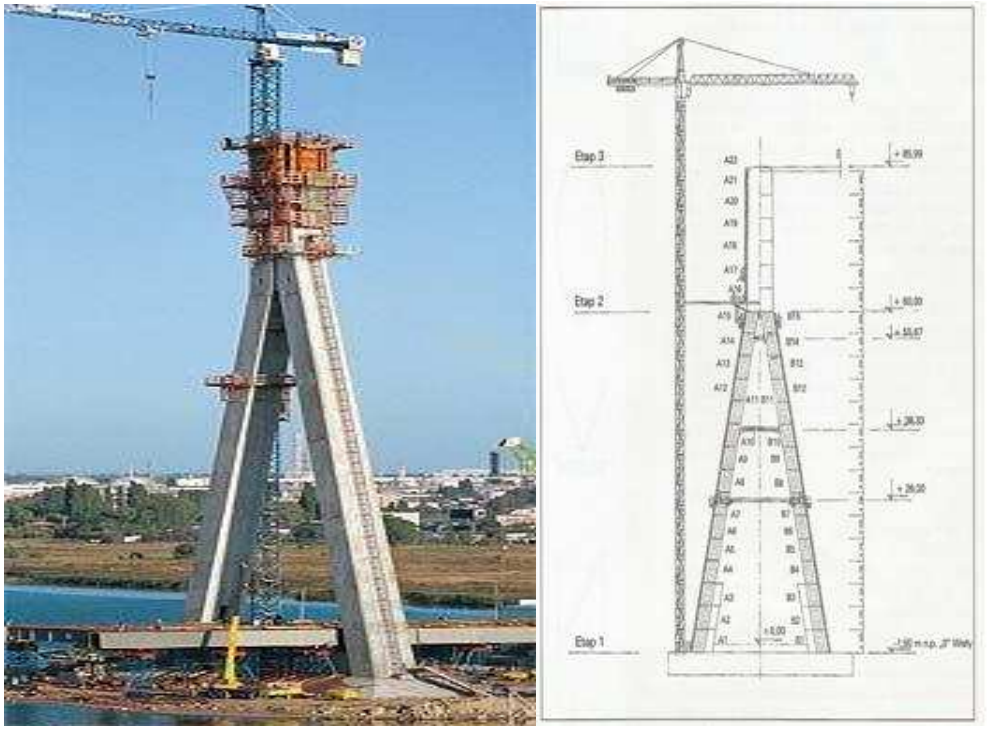


Fig. 15. View of bridge support structure (pylon) under construction (Świętkorzyski bridge in Warsaw).

Chair of Engineering Geodesy and Control-Measuring Systems has also a tradition in polar research. Employees of the Chair carried out measurements in the vicinity of the Polish station on Spitzbergen as well as in the Antarctic. The research carried out in those regions was described in a separate article published in the jubilee issue of „Reports on Geodesy and Geoinformatics".

The thematic scope of research realised by Chair of Engineering Geodesy and Control-Measuring Systems shows that research work related to geodetic engineering measurements and geodetic monitoring is carried out with high intensity, resulting in technological advancement and implementation of new or improved measurement solutions and methods of measurement result development.

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