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# Monitoring and analysis of the displacements of slender structures: A case study of the Wroclaw Iglica

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**Summary**

The article presents an analysis and comparison of geodetic methods used for the measurement and monitoring of slender structures such as chimneys, towers, cooling towers, and power line poles. Due to their slender geometry and considerable height, these structures are highly sensitive to environmental influences, including wind, temperature variations, and ground settlement. The study discusses the evolution of measurement techniques – from classical tacheometry and levelling, through satellite-based GPS and GNSS systems, to modern terrestrial laser scanning (TLS) and digital photogrammetry.

Recent research indicates integrating multiple surveying methods, known as a hybrid approach, guarantees improved accuracy and reliability of measurement results. The measurement of verticality of the Wrocław Iglica, a representative slender structure, is an example of the use of the described methods. Due to its geometry and the conditions in the field, a tacheometric survey was conducted to determine vertical axis deviations under different sunlight conditions. The results confirmed noticeable deflections of the structure's top throughout the day, demonstrating the influence of thermal factors on its stability.

The analysis of both literature and measurement shows that the most effective approach to monitoring slender structures is the integration of data from various geodetic techniques. Such hybrid monitoring ensures a comprehensive assessment of the structural stability and durability of slender constructions over time. The results highlight the importance of continuous geodetic monitoring as a key factor in ensuring the safety and reliability of engineering structures.

**Keywords**

construction monitoring • verticality • deflection from the axis • slender structures • tachymetric measurement

## 1. Introduction

Slender (or tower-like) structures are all buildings whose height significantly exceeds their maximum width – usually at least five times. Tower structures include, for example: industrial chimneys, power poles, hyperboloid cooling towers, television towers, pressure or observation towers, cooling towers, lighthouses, silos and various types of masts. They play a key role in industrial and municipal infrastructure. They are characterised by their great height and relatively small cross-section, which makes them particularly sensitive to environmental (wind, temperature fluctuations, ground settlement, precipitation) and internal (material ageing) influences. For this reason, they require systematic geodetic monitoring to assess their stability and verticality. This issue has been discussed in geodetic studies for many decades, and with the development of measuring instruments and calculation techniques, significant progress has been made in measurement methods.

Classic tachymetric measurements provided the basis for checking the verticality of tall industrial chimneys. Kamiński and Matwij [2016] described procedures for using tachymetry to determine the verticality of structures, emphasising the advantages of the method in conditions of limited access to the object. Łyszkowicz and Gawałkiewicz [2015] presented a case study in which tachymetry played a key role in assessing the verticality of an industrial chimney. These studies demonstrated that with appropriate measurement organisation, it is possible to achieve high precision, but the time-consuming nature and difficulty of recording dynamic deformations remain a limitation.

Satellite systems were one of the first tools enabling real-time monitoring of structural deformation. Lovse et al. [1995] and Knecht and Manetti [2001] proved that GPS can be used for dynamic monitoring of deformations in tall structures. Park et al. [2008] used GPS to observe the effect of wind on the vibrations of skyscrapers, while Liang et al. [2020] analysed the resistance of power poles to wind loads using GNSS. Contemporary studies emphasise that although the precision of GPS/GNSS is limited compared to tachymetric or TLS measurements, this technology permits long-term observations [Li et al. 2014, Hu et al. 2023].

The greatest progress in research on the geometry of slender structures is related to the use of terrestrial laser scanning. Kozłowski and Ligas [2014] and Głowacki et al. [2016, 2022] demonstrated the reliability of TLS in diagnosing the geometry of chimneys [Kregar et al. 2015, Muszyński et al. 2017, Siwiec et al. 2022], wind turbines and cooling towers. Makuch (2025) developed this issue further by employing TLS to analyse geometric imperfections in hyperboloid cooling towers. Beshr et al. [2023] presented a method of projecting coordinates from TLS onto a vertical plane to analyse deformations of a cooling tower, and Pleterski et al. [2024] used the RANSAC algorithm to assess the deviations of chimneys from the vertical. Meanwhile, Matwij et al. [2024]

emphasised the importance of semi-automatic point cloud analysis in examining the verticality of structures with complex geometry. Vezočnik et al. [2009] showcased the use of TLS in long-term monitoring, highlighting its millimetre-level precision.

Modern approaches integrate TLS with photogrammetry and LiDAR systems. Siwiec et al. [2022] demonstrated that combining photogrammetry with TLS increases the reliability of measurements of chimney verticality. Spadavecchia et al. [2023] and Kaartinen et al. [2022] presented the use of LiDAR for monitoring civil infrastructure. Ma et al. [2023] and Chen et al. [2023] developed solutions based on 2D and 3D imaging that allow for the automatic detection of power pole tilts.

There is a growing emphasis in the literature on the need to combine different techniques within a single diagnostic system. Pandžić et al. [2016] as well as Bieda and Mikrut [2017] suggest that the integration of TLS and total station surveying eliminates visibility gaps and improves the accuracy of analyses. Proszyński and Kwaśniak [2015], and Głowacki [2022] draw attention to the significance of comprehensive monitoring systems that combine tachymetric data, GNSS, and inclinometric measurements. Recent studies [Alkady et al. 2023, Makuch et al. 2024, 2025] propose the implementation of automatic and semi-automatic methods for point cloud analysis, which considerably reduces the risk of interpretation error.

An important aspect of the research is the analysis of the impact that environmental factors have on the stability of structures. Breuer et al. [2008] investigated how sunlight and wind affect the deflection of a television tower in Stuttgart. Kijewski and Kareem [2001] and Mendis et al. [2007] presented the results of full-scale studies on the effects the wind has on skyscrapers and tall structures. Dhoolappanavar et al. [2024] expanded on this topic by analysing the impact of wind and soil-structure interaction on reinforced concrete chimneys.

## 2. Description of the surveyed structure

The subject of the research is the Wrocław Iglica (Wrocław Spire) located in front of the Centennial Hall in Szczytnicki Park on Wystawowa Street in Wrocław, in Poland. It played a key role during the Exhibition of the Earth on 3 July 1948, when the Iglica was officially unveiled. Since then, it has been through many renovations, which have reduced its current height from the original 106 metres to 90.3 metres. It is constructed of steel elements with supports based on three concrete foundations [Jeziorna 2020].

Currently, it is a landmark in Wrocław (Fig. 1), attracting many tourists every year and serving as a focal point for one-off and regular events that bring the local community together [Jeziorna 2020].

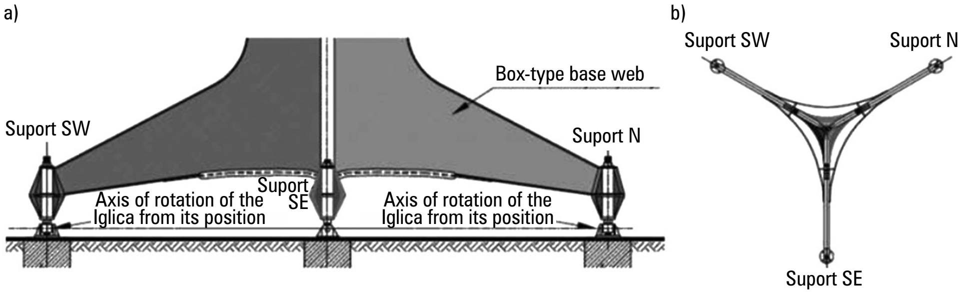
The Iglica is classified as a slender structure due to its design (Fig. 1). Such structures are subject to various external loads that cause their movement and deformation. These loads are the result of the weight of the structure, ground settlement, changes in groundwater levels, the wind, temperature and physicochemical processes affecting the construction materials. Potential defects during the construction process may also contribute to these loads. Due to these factors, slender structures should be subject to systematic geodetic observations performed at specific intervals. Analysis of the observation results allows for an assessment of the durability of the structure, taking into account the clear distinction in displacements between uniform foundations and flexible cores. This distinction is a key element in the proper interpretation of the obtained results of structural displacements [Gocał 2010].

Source: Authors' own study

**Fig. 1.** View of the Iglica tower against the backdrop of the Hala Stulecia (Centennial Hall) – Wrocław

The first 70 metres of the structure is made up of 12 segments in the form of a ribbed sheet metal plate, expanding in three directions. The cross-section of the core narrows towards the top, and after exceeding a height of 70 metres, the Iglica becomes a tubular cross-section, also narrowing towards the top. The original weight of the Iglica was approximately 44 tonnes. The core of the structure rests on a three-legged base and is the widest element connecting the structure to the foundations (Fig. 2). The base mounts in the foundations are arranged at the vertices of an equilateral triangle with sides 12.124 m long, inscribed in a circle with a radius of approximately 14 m.

The design of the Iglica allows it to be positioned horizontally by rotating the structure around the axis connecting the SW and N pillars. The pillars running parallel to the plane of rotation of the Iglica are connected by movable joints, while fixed joints are used in the direction of rotation. This design allows for the necessary periodic maintenance work, in particular the refreshing of anti-corrosion coatings. To date, the Iglica has been laid horizontally three times, in 1963, 1979 and 2016 [Czapliński et al. 2018].

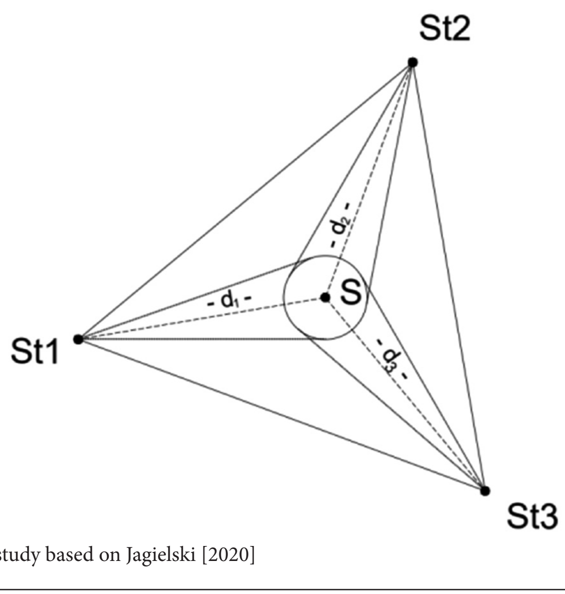



Source: Czapliński et al. [2018]

**Fig. 2.** Three-legged base of the structure: a) side view fragment, b) cross-section

## 3. Measurements performer

A key requirement for any tower structure is to maintain the rectilinearity and verticality of its geometric axis. Deviations of the structure's axis from the vertical may be attributable to internal factors, such as construction errors, the structure's own weight, asymmetrical subsidence of the foundations, corrosion and ageing of materials, as well as external factors, e.g. the impact of wind, aggressive chemical effects of atmospheric pollution and exhaust fumes (this concerns chimneys in particular), changes in sunlight and temperature inside and outside the building, affecting the ground by digging deep excavations and erecting buildings in the vicinity of the tower [Jagielski 2020].

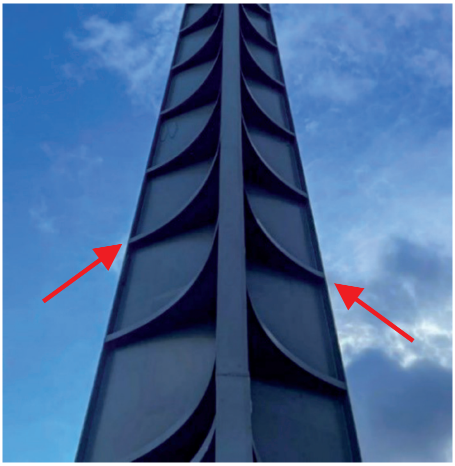



Source: Authors' own study based on Jagielski [2020]

**Fig. 3.** Standard positioning of stations for testing the verticality of a slender structure

In order to measure the deflections of the Iglica, it was necessary to select the most appropriate measurement method for the object under study. The trigonometric method was adopted, using three Trimble C5 2" tachymeters. The measurements should be taken from conveniently and evenly spaced stations with respect to the structure. This is most often done from three stations (Fig. 3 – St1, St2, St3), which, if possible, should form a shape similar to an equilateral triangle, where the centre of balance is the core of the object S.

The surveyed structure is located in the centre of Wrocław, which is densely built-up and surrounded by green infrastructure. For this reason, the use of techniques other than the traditional ones (such as trigonometric method using a tachymeter) to check the verticality of the structure could be very problematic and time-consuming in terms of planning and performing the measurements. The main difficulty would be maintaining an appropriate distance from the stations to the structure so that the entire structure is visible from each station (too close – the top is not visible, too far – imprecise determination of the position of the tip of the Iglica). In addition, the Iglica does not have clearly marked observation floors on each side that overlap with each other (Fig. 4 – red arrows), as is usually marked, for example, on an industrial chimney.

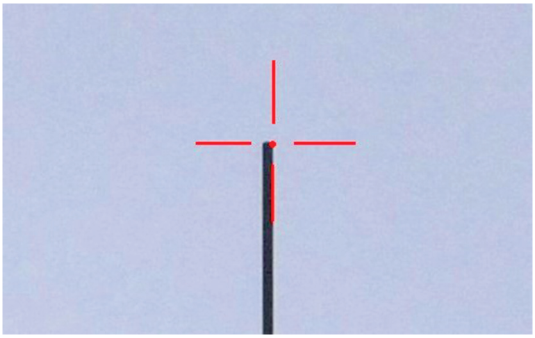


Source: Authors' own study

**Fig. 4.** Close-up of the Iglica from both sides

For these reasons, it was decided to make partial use of the surrounding tangents method and measure only the tip of the structure (on its left and right sides – Fig. 5) at regular intervals. Observations were made from 6 a.m. to 6 p.m. synchronously from three stations every 15 minutes. When using this measurement method, it was important that only the tip of the Iglica was visible, not necessarily the entire object.

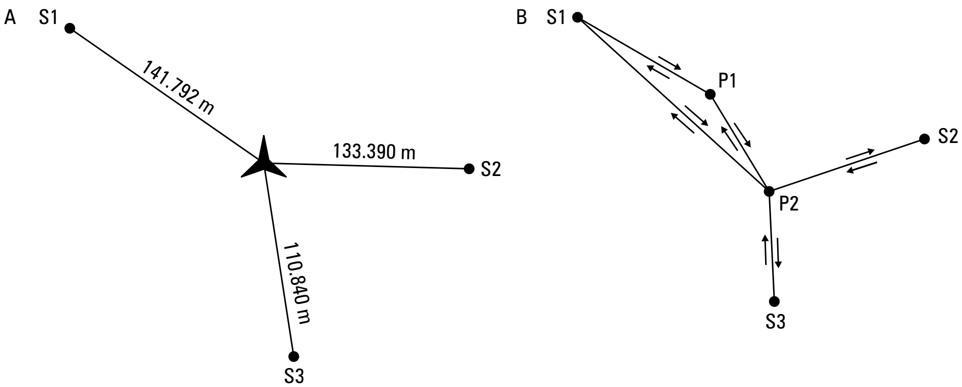
A single observation involved aiming the crosshairs of the reticle at the intersection of the Iglica with the upper base of the tubular cross-section (Fig. 5). From each station, observations were directed at the tip of the structure on the right and left sides, in two positions of the telescope.



Source: Authors' own study

**Fig. 5.** The way the telescope was directed at the right side of the tip in the image of the actual top of the Iglica

A field survey was conducted in order to establish a measurement grid. Three observation stations (S1, S2, S3) were set up to measure the deflections of the Iglica's tip. These stations were unevenly distributed around the object (Figs. 6, 7) due to terrain conditions that prevented the formation of an equilateral triangle.

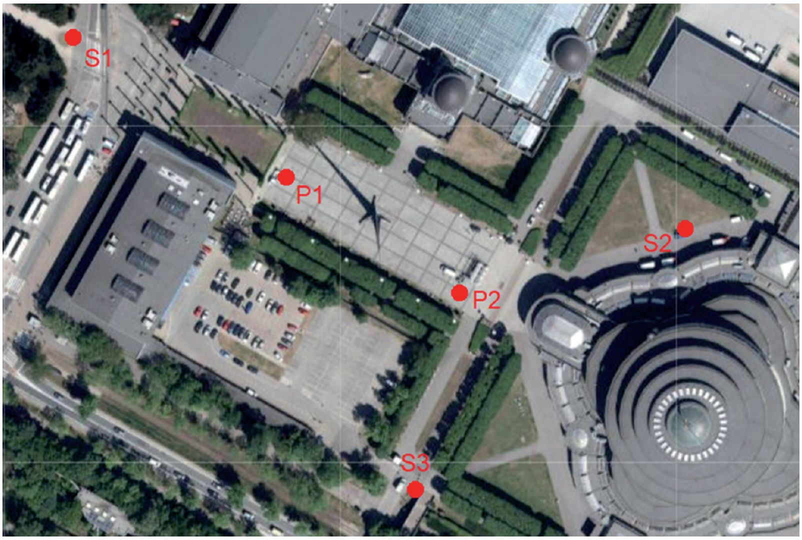



Source: Authors' own study

**Fig. 6.** A. Sketch of the arrangement of stations around the Iglica with distances. B. Illustration of the way the measurement grid was determined

As mentioned above, it was not possible to position the points evenly due to the lack of visibility between neighbouring stations, so two auxiliary points were introduced. The final measurement grid consisted of three stations and two connecting points (Fig.

6B). Each of them was stabilised with a 50 mm long steel pin. The location of the grid points (S1, S2, S3) and auxiliary points (P1, P2) is shown in Figure 7 on a fragment of the orthophotomap.




Source: Authors' own study based on https://geoportal.wroclaw.pl/

**Fig. 7.** Layout of the local grid relative to the structure against the background of an orthophotomap

A total of 49 measurements of the top of the Iglica were taken simultaneously from each station. Each observation was carried out in two telescope positions, aiming from two sides at the intersection of the object's generatrix with the upper surface of the Iglica's tubular cross-section, using three Trimble C5 2" electronic tachymeters.

## 4. Elaboration of measurement results

After taking measurements according to the diagram (Fig. 6B), the measurement data was compiled. The first measurement taken at 6 a.m. was used as a reference point for the observations. The deviations of the coordinates from the reference point were also calculated. All calculations (precise adjustment of horizontal and vertical points) were made in the C-geo programme. The following observation errors were adopted during the adjustment:

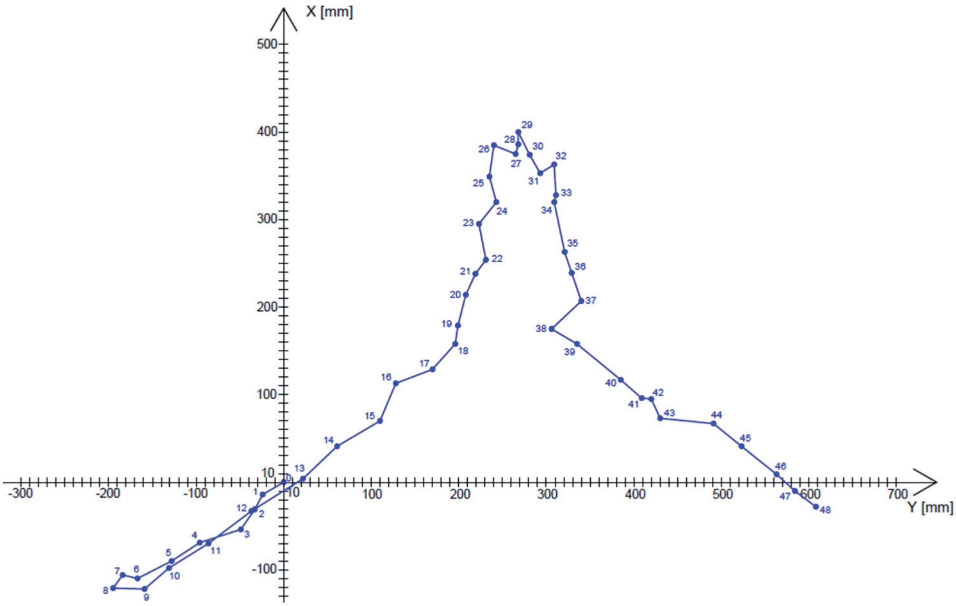
- error in direction measurement $m_k = 0.0010^g$,
- error in distance measurement $m_d = a + b \cdot D$, where $a = 0.020$ m and $b = 0.020$ m.

The average observation error from the precise situational adjustment was: $m_0 = 1.03216$.

The next step was to align the height of the measurement grid points. This was done by calculating the trigonometric elevation between the grid points based on observations. During the alignment, the elevation error was taken as the product of the horizontal length and *mdH* (*mdH* = 0.0140 m was determined). The average error from the precise height alignment was: *m*0 = 1.08099.

The mean direction was calculated on the basis of measurements, which is equal to the target oriented towards the centre point of the Iglica's top. In addition, the radius of the Iglica's top was determined from the measured angles (directions along the right and left tangents) and the distance from the station to the centre of the top [Jagielski 2020].

The first measurement taken at 6 a.m. was adopted as the reference level for the observations. The deviations of the coordinates from the adopted reference point for the top of the Iglica were also calculated. Figure 8 shows a graph of the deviations of the mean adjusted coordinates of the top of the Iglica in the XY plane. The figure includes the numbers of successive measurements from 0 to 48, which corresponds to measurements taken at 15-minute intervals.




Source: Authors' own study

**Fig. 8.** Graph of deviations of the mean adjusted coordinates of the Iglica's apex in the XY plane

After processing the results, the significance of the deviations of the top of the Iglica was assessed for each measurement (Table 1). This was calculated based on the average coordinates determined for each hour in the XY plane. The triple error of the apex position obtained from the precise adjustment was assumed for the assessment. The calculated deviation vector was also subjected to a significance analysis.

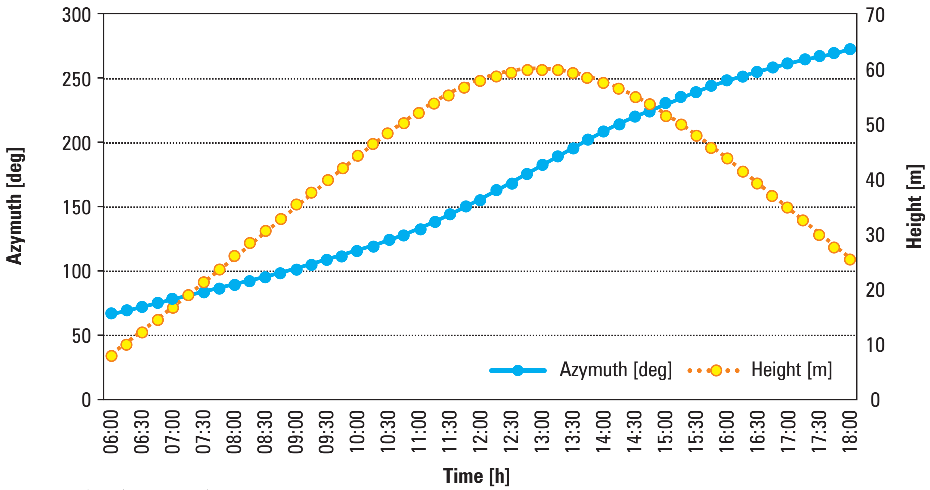
**Table 1.** Assessment of the significance of deviations of the top of the Iglica for each measurement – selected points

| No | *h* | *X* [m] | *mx* [m] | 3 · *mx* [m] | Significant | *Y* [m] | *my* [m] | 3 · *my* [m] | Significant | Vector lenght *dl* [m] | *mp* [m] | 3 · *mp* [m] | Significant |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 06:00 | 0.000 | 0.042 | 0.126 | No | 0.000 | 0.039 | 0.117 | No | 0.028 | 0.057 | 0.171 | No |
| 1 | 06:15 | −0.014 | 0.042 | 0.126 | No | −0.024 | 0.039 | 0.117 | No | 0.019 | 0.057 | 0.171 | No |
| 2 | 06:30 | −0.031 | 0.042 | 0.126 | No | −0.033 | 0.039 | 0.117 | No | 0.028 | 0.057 | 0.171 | No |
| 3 | 06:45 | −0.054 | 0.042 | 0.126 | No | −0.049 | 0.039 | 0.117 | No | 0.049 | 0.057 | 0.171 | No |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| 37 | 15:15 | 0.207 | 0.042 | 0.126 | Yes | 0.340 | 0.039 | 0.117 | Yes | 0.047 | 0.057 | 0.171 | No |
| 38 | 15:30 | 0.175 | 0.042 | 0.126 | Yes | 0.306 | 0.039 | 0.117 | Yes | 0.034 | 0.057 | 0.171 | No |
| 39 | 15:45 | 0.158 | 0.042 | 0.126 | Yes | 0.335 | 0.039 | 0.117 | Yes | 0.065 | 0.057 | 0.171 | No |

Source: Authors' own study

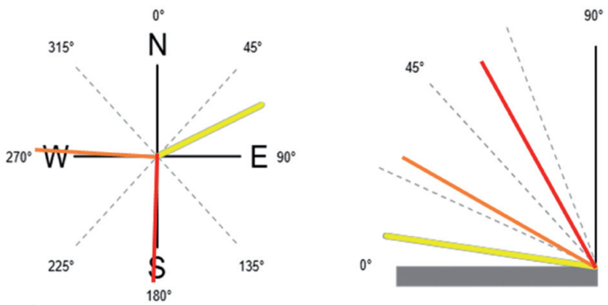
Since the deviations proved to be significant (Table 1), the next step was to analyse the cause of these movements. The results suggested that atmospheric conditions may have influenced the movements of the structure. As it was a windless day, sunlight was considered to be the primary cause of the deviations. In order to conduct analyses for the measurement area as well as for the date and time of the measurements, the height and azimuth of the sun were determined from astronomical data.

The graph in Figure 9 represents the average height of the sun (from three locations; yellow) and the azimuth of the sun at a given hour. The measurement was taken over 12 hours (6 a.m. to 6 p.m.), while the length of the day is over 16 hours (5 a.m. to 9 p.m.). The beginning and end of the graph are not equal to 0 due to differences between the measurement time and the length of the day. The values of the sun's azimuth at a given hour are marked in blue (Fig. 9). Figure 10 shows the position of the sun relative to the adopted coordinate system and relative to the horizontal plane.




Source: Authors' own study

**Fig. 9.** Average height and azimuth of the sun during measurements




Source: Authors' own study

**Fig. 10.** Azimuth (left) and height of the sun above the horizon (right)

In Figure 10, the azimuth (measured in degrees clockwise from midnight) and the height of the sun above the horizon (on the right) at 6 a.m. are in yellow, while red indicates 2 p.m., when the sun was at its highest, and orange indicates when the measurement was completed at 6 p.m.

## 5. Analysis of measurement results

The final result of the measurements of the top of the Iglica is the 49 XY coordinates of the centre point of this top. Analysing the graph and the calculated deviations, one can notice very large deviations of the top from the adopted reference level, which was the first measurement at 6 a.m. These deviations are caused by the unusual design of the structure, with its great height and narrowing width. In addition, weather conditions, especially the direction of sunlight and the strength and direction of the wind, are important factors affecting the movement of the top of the Iglica.

For the X axis, the deviations ranged from −0.122 m to 0.400 m, and for the Y axis from −0.195 m to 0.608 m, while the average deviation was 0.161 m. The displacement vector between the first and last measurements is 0.698 m. The largest displacement of the Iglica's top was 0.808 m, occurring between measurement no. 8 at 8 a.m. and the last measurement at 6 p.m. As part of the measurement compilation, the diameter of the top was calculated to be approximately 0.095 m.

When analysing the graph of the average deviations of the coordinates of the Iglica's top in the XY plane (Fig. 8), it can be noticed that it is similar to the cross-section of the Iglica's base (Fig. 2). One of the Iglica's supports is facing north. Comparing this with the graph, it can be assumed that the X axis is close to the north direction and the Y axis to the east direction. Therefore, it can be assumed how the sun's rays affect the position of the top at a given time.

Taking into account the analysis of the significance of the structure's tip deflections, it was noted that in the X axis, significant deflections constitute half of the measurements, while in the Y axis, this number is significantly higher. In the case of the deflection vector, significant deviations occur only in the last measurement.

The statistical analysis of the obtained results began with determining Pearson's correlation matrix. Pearson's correlation coefficient *r* is given by the following formula:

$$r = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\cdot\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2 \cdot \sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}} \quad (1)$$

where:

$x_i, y_i$ – pairs of variables for which correlation is sought ($n = 49$),
$\overline{x}, \overline{y}$ – mean values of variables.

The correlation analysis took into account the azimuth and height of the sun, as well as the value and azimuth of the deflection of the top of the Iglica. Table 2 below presents the correlation matrix for selected variables.

**Table 2.** Pearson's correlation matrix

| | $A_{sun}$ | $H_{sun}$ | $dl_{Iglica}$ | $A_{Iglica}$ |
|---|---|---|---|---|
| $A_{sun}$ | 1.000 | 0.414 | 0.882 | −0.358 |
| $H_{sun}$ | 0.414 | 1.000 | 0.557 | −0.603 |
| $dl_{Iglica}$ | 0.882 | 0.557 | 1.000 | −0.260 |
| $A_{Iglica}$ | −0.358 | −0.603 | −0.260 | 1.000 |

Source: Authors' own study

The correlation matrix analysis reveals that the strongest correlation occurs between the displacement of the top of the Iglica and the direction of the sun. It can be assumed that this is related to the sun's thermal radiation.

The analysis also applied the method of multiple linear regression. The general correlation in this analysis is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \tag{2}$$

where:

$Y$ – explained variable,
$X_1, X_2, X_3$ – explanatory variables,
$\beta_0, \beta_1, \beta_2, \beta_3$ – regression coefficients,
$\varepsilon$ – random element.

Based on the matrix (Table 2), a multivariate regression analysis was prepared. The displacement vector of the Iglica's apex was taken as the explained variable, and the remaining three variables as explanatory variables. The calculations were performed in Matlab R2025b using the defined linear regression function 'fitlm'. As a result of the calculations, a report was obtained including:

- Number of observations $n = 49$.
- Error degrees of freedom $k = 45$.
- Root mean squared error of the model's fit RMSE = 0.064.
- R-squared coefficient of determination $R^2 = 0.865$.
- Significance test $F = 96.1$ and $p$-value = $1.37 \times 10^{-19}$ ($F$-statistic vs. constant model).

When analysing this report from regression calculations, it should be noted that a significant result has been obtained, i.e. there is a correlation between the explained variable (displacement vector) and the other three explanatory variables. The significance test indicates that all variables are statistically significant. The model used explains approximately 86% of the displacements derived for the Iglica, and the resulting fit error is very small.

## 6. Conclusions

A review of the literature indicates the evolution of surveying methods from classical angular and levelling techniques, through electronic total stations and GNSS systems, to advanced TLS and digital photogrammetry methods. The current trend is to integrate multiple techniques for more accurate and reliable monitoring. In engineering practice, hybrid solutions have proven to be the most effective, providing both ongoing control of vertical deviations and long-term monitoring of structural stability.

Slender structures are unique from the perspective of geodetic control measurements. These include industrial chimneys, steel towers, power poles and such unusual structures as the Iglica tower. These structures are characterised by their specific design and are particularly susceptible to external factors such as changing weather conditions (sun, wind, precipitation) and internal factors (material ageing).

In order to monitor their stability, the position of the structure's axis and its deviation from the vertical are assessed using geodetic and photogrammetric methods. Unfortunately, in the case of the Iglica, it was not possible to use laser scanning due to the distance between the scanner stations and the object, as well as the height of the Iglica. It is a structure with a specific design, which narrows significantly towards the top, which would present a major problem when measuring such a small steel surface at the very top with a scanner. Using scanning is also problematic due to the costs involved, the significantly longer data processing time (clouds) and the fact that measurements are taken from only one station (from one side rather than three as in the case of tachymetry) at specific intervals (every 15 minutes) during a 12-hour measurement. Analysing the obtained results, it can be concluded that the assumptions made regarding the measurement results proved to be correct. This is demonstrated by the fact that in each subsequent measurement the top of the Iglica deviated significantly from the adopted reference level (from 6 a.m.), when the sun's rays were not yet falling on the object.

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