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ORIGINAL ARTICLE

Influence of reference stations on the stability of the geodetic control network during deformation determination in the area of Kadzielnia in Kielce

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Abstract

Observations of land surface deformation are one of the important tasks of surveying, especially in landslide areas. They concern the determination in time of the magnitude of the deformation, on the basis of a stable reference system based on a geodetic control points. The whole measurement process can be divided into two parts. One part concerns the observation of reference points (geodetic control points) and the other the observation of the object itself. In the first, in addition to classical methods, GNSS (Global Navigation Satellite System) techniques based on reference stations are used. In the second, common observation methods such as laser scanning or photogrammetric methods using Unmanned Aerial Vehicles (UAV) are used. These observations are carried out in a specific time period in relation to the aforementioned geodetic control points. An area such as Kadzielnia in Kielce is covered by a long-term observation programme. A key element is the survey of the constancy of the geodetic control points, which are located in the epicentre of the survey. The survey of the constancy of the control points at Kadzielnia was based on a static method using SmartNet stations. Taking into account the fact that reference stations are treated as error-free reference points and that they operate 24 hours a day, it was decided to study the variability of their position over a longer period of time, as well as to determine the influence on the geodetic control points and to observe the deformation of the object during the measurement cycles.

Key words: Keywords: reference stations, GNSS observations, control points.

1 Introduction

The problem of landslides and the hazards they pose is a world-wide issue. In densely built-up areas, this phenomenon poses a real threat to human life and human health. It may also cause serious damage to technical and transport infrastructure (Yu et al., 2022). In addition, landslides are a factor in land degradation, preventing further use of the land in the form of crops or buildings. The problem of landslides affects many countries. One of them is China where there are many landslide-prone areas. Ongoing studies Yu et al. (2022); Xiong et al. (2023) based on remote sensing and global GPS were conducted to realise a comprehensive early identification, prediction and early warning, which can effectively prevent disasters. In India, too, landslides are one of the major natural disasters. They are responsible, each year, for an estimated US$66 million damage in property and the death of 200 people in the Himalayan and Western Ghats region (Kumar and Ramesh, 2022; Yadav et al., 2020). One method of observing earth mass movements is GNSS. In the study Tiwari et al. (2018), GNSS networks were used with the aim of detecting ground surface displacements using survey points for the TLS (Terrestrial Laser Scanning), GNSS and RTS (Robotic Total Station) survey technologies used. An analysis of the GNSS geodetic network, which also worked as the control points for TLS and RTS, shows that the positions of the points in the RTS and TLS surveys changed, so corrections were made to the coordinates to

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eliminate surface bias (Tiwari et al., 2018). The use of GNSS stations to observe the control points and the use of an absolute reference system (ETRF2000) is a good idea, as it allows comparison with other data available for the landslide (Barbarella and Fiani, 2013). Also, time series analyses show that the quality of solutions does not differ from that of other areas. National GNSS networks can realise a stable reference for the whole area, for different geodetic measurements (Figurski et al., 2010). However, study Savchuk and Tadyeyev (2020) has pointed out that reference systems, due to the influence of various factors, are subject to changes over time in terms of violation of their basic geometrical and physical conditions. Among violations of these conditions, tectonic activity of the Earth has most influence. Violation of such conditions causes deformation of the reference system, which further affects the geodetic control points. Reference systems such as the ITRS (global system) or ETRS (European system) are created based on continuous monitoring of the Earth using satellite techniques. They ensure the stability of the datum, especially considering the influence of tectonic processes at a local level (Savchuk and Tadyeyev, 2020).

One of the areas where landslide movements occur is Kadzielnia, located in the centre of Kielce. The site is a strict inanimate nature reserve, being a remnant of the Devonian limestone exploitation, which lasted from the 17th century until 1962. As a result of intensive quarrying, all that is left of the original hill is the eastern slope, the remnants of the south-western slope with an adjoining heap (now known as the Scouts' Hill) and the Geologists' Rock, separated by deep excavation (Garus et al., 2007). The existing condition, despite the passage of several decades, still poses a certain threat, both to the landscape of the reserve and to the people living there. The slopes of the quarry, which have been subject to quarrying, remain far from stable. Therefore, there is a real threat of activation of landslide processes that are often violent and unexpected. Landslide activity is evidenced, for example, by the accumulation of fragments of rock masses at the foot of the quarry walls. Therefore, it is necessary to monitor the changes that occur on the slopes to identify the risk of landslide activity. Comprehensive monitoring of a given area requires surveys in various speciality areas, including geodetic observation, which must take into account several stages:

1) Establishment and measurement of the geodetic control network.
2) Observations to test the constancy of the geodetic control network.
3) Observations of the site using different methods: polar (scanning total station), scanning and photogrammetric methods using an unmanned aerial vehicle (UAV).
4) Comparison of results between measurement cycles.
5) Analysis of the results obtained.
6) Determination of the magnitude of the deformation.

This last stage is influenced, among other things, by the results of comparisons between measurement cycles, which in turn are possible due to the use of static GNSS observations of geodetic control points ensuring adequate accuracy and stability (testing the constancy of the geodetic control network). The constancy survey of the control points is based on the SmartNet network of reference stations. In view of the above, the main objective of this publication is to investigate the influence of reference stations as reference points on the constancy of the geodetic control network.

Figure 1. Landslide movements in Kadzielnia (Krawczyk, 2021)

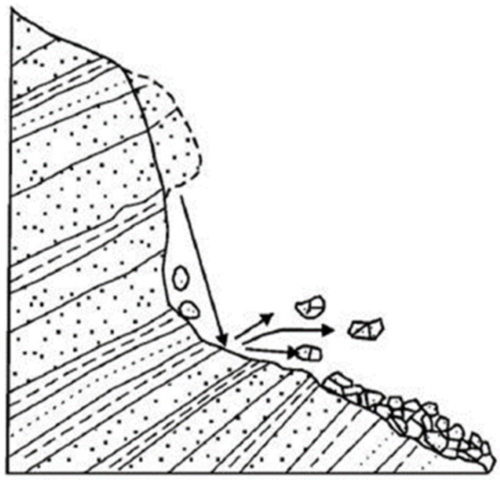


Figure 2. Breaking away of some rock masses (National Geological Institute, 2008)

2 Geodetic monitoring of landslides

The studies of landslides located in the Kadzielnia area by means of geodetic measurement methods were aimed at determining the magnitude of the mass movements of rock fragments (Figure 1).

The basic issue of landslide monitoring is the selection of measurement techniques suitable to obtain the expected result of the observations, the determination of the expected accuracy and the frequency of the observations of the object. At the same time, it is necessary to determine the accessibility and the possibility of entering the object according to the safety rules of work. In the case of an area of active landslide, threatening human life (especially one located near inhabited places), observations should be carried out continuously and with high accuracy, which in turn implies the need to obtain an adequate amount of data. In the case of the measurement of a periodic landslide, which is located away from human habitats, the accuracy may be lower and observations made at longer intervals (several months). Landslides in the Kadzielnia area are classified as periodic.

The studied landslides in the area of the "Kadzielnia" Reserve are rock walls built of Devonian limestone with a very steep slope. This, among other things, is the reason for the so-called rockfalls (Figure 2). This limits the possibility of using certain measurement methods. The choice of instruments used for measurement depends mainly on the expected accuracy. Therefore, it is important to determine the required and, at the same time, sufficient accuracy of the obtained measurement results (Maciaszek et al., 2015). The choice of time intervals between successive measurement series depends on the knowledge of the causes of the resulting deformations. In the case of landslide-type ground surface movements, it is optimal to record the occurring processes continuously in time.

The following methods were selected to monitor the landslide in Kadzielnia:

- GNSS techniques (Figure 3a) – static measurements (to determine the coordinates of the network points),
- laser scanning of the landslide surface with a laser scanner (Figure 3a),
- scan of the surface of the landslide using a scanning total station (Figure 3b),
- photogrammetric – images obtained using a UAV (Figure 3c).

The comparison of results between measurement cycles (Figure 4) was made using static GNSS observations of geodetic control

(a) Satellite techniques combined with a laser scanner

(b) Total station surveying

(c) Photogrammetric technique using a UAV (Krawczyk, 2021)

Figure 3. Measurement equipment

Figure 4. Comparison of measurement results (shape-to-shape) (Krawczyk, 2021)

(a) **(b)**

Figure 5. Survey control points (a) and geodetic control point (b) at the Kadzielnia site (Krawczyk, 2022)

points ensuring adequate accuracy and stability. Differences between measurement cycles (comparison of geochromes of points) ranged from a few to several tens of centimeters. The constancy test of the control points was performed before each measurement cycle.

3 Testing the stability of the control points

Monitoring should be based on a permanently stabilised grid of survey points (control points) in the ground around the landslide. Optimally, the control points should be outside the influence of possible mass movements. Geodetic control points were established at the Kadzielnia site in the zone of influence itself. The control points provide visibility between neighbouring points (the lush vegetation complicating its shape cannot be removed due to its location in a nature reserve). A total of four metal poles were fixed in the reserve, acting as warp points. Stabilization was carried out using two 2-metre poles, 20 cm in diameter, with threads point No.1401 and 1402 (which allows a prism to be mounted and the instrument to be set up without the need for a tripod, i.e. with forced centring) (Figure 5b), and two 1.5-metre pipes (Points No. 1404, 1403), 8 cm in diameter, which allow a prism to be mounted but without the possibility of setting up the instrument directly on the point. Stabilization of the poles took place closer to the landslides. Point No. 1405 was additionally stabilised as a control point in the form of a target plate. The distribution of the grid points is shown in Figure 5a (Krawczyk, 2022)

As already mentioned, the geodetic control point at Kadzielnia is located in the very zone of influence, therefore, it is very important and necessary to test the constancy of the points forming the control network. However, when studying the constancy of the control points (Figure 5a), we have to answer a fundamental question. Which values of change are to be considered as deformation and which are the result of unavoidable observation errors? The basic way to solve this problem is to determine the observation error on the basis of independent measurements and to carry out a survey of the constancy of the control points, as a result of which a possible correction of the coordinates of the control points can take place.

Observations carried out for many years at GNSS reference stations provide the basis for reliable determination of coordinates. Therefore, the study of the stability of the control points in Kadzielnia was based on such stations. They record continuous (permanent) signals coming from satellites at a fixed measurement interval. The recorded data are made available to interested users (Banasik et al., 2008). The appropriate location of the reference stations provides the opportunity for full use. The most common use of reference station networks is the measurement of RTK.

The constancy test of the control points was based on four reference stations of the SmartNET network located in the following: Kielce, Jędrzejów, Szydłów and Skarżysko-Kamienna (Figure 6). Hourly measurements (sessions: 1÷1.5 h) were made at the control points using the static GNSS method. The coordinates of the points were calculated in relation to the SmartNET.

From the entire grid of the control points, points 1401 and 1402 were used (Figure 5a) for the development. Figure 6 shows an example of the development of point 1401.

The use of GNSS technology to test the constancy of the control points requires:

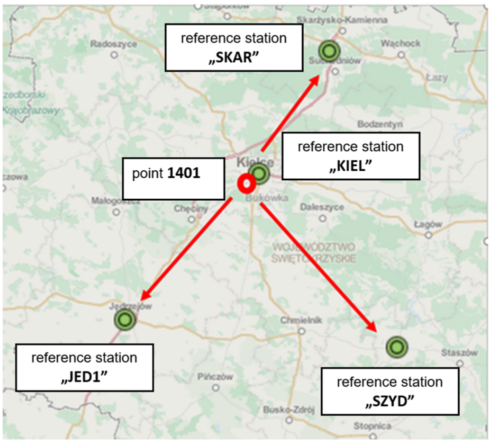


Figure 6. Reference stations for determining the position of control point No. 1401 (Krawczyk, 2022)

Table 1. Summary of error values in particular years (Krawczyk, 2021)

year	error values [mm]			
	m_x	m_y	m_p	m_H
2014	5	13	14	20
2014	11	4	12	19
2014	3	9	10	21
2015	2	2	3	17
2016	3	9	10	21
2019	9	4	10	11
average	**5,5**	**6,8**	**9,8**	**18,2**

- determining the error in the specification of the coordinates of a single point,
- determining the stability of reference stations,
- determining on this basis the accuracy criterion, exceeding of which indicates the occurrence of a displacement of control points,
- based on the criterion – determination of probable magnitude of displacement of a control point.

The accuracy of determination of coordinates of control points and their changes with the use of satellite observations may be determined, among others:

- from data collected, e.g. from reports within the reference station network,
- by making multiple (repeated) observations at the same points and comparing the results;
- by observing simulated changes in the position of the point.

The determination of the average errors in specifying the position of the control points was carried out on the basis of the results of the measurement with the static method, using SOKKIA and STONEX receivers. The following errors, in Table 1, were obtained from the measurements.

4 Analysis of the variability of the positions of the reference stations as reference points

The determination of the variability of the positions of the reference stations in the SmartNet network used as reference points of the control points was based on data from the GNSS Data Research Infrastructure Centre co-financed by the European Regional Development Fund (ERDF) (EPNACC WAT, 2023). The Center presents information on the current location of Polish GNSS reference stations providing observations. Every day around 5pm, the current coordinates expressed in the current implementation of the ITRS (International Terrestrial Reference System) - ITRF2014 - are determined. The coordinates are then transformed into the ETRF2000 system and compared with the coordinates reported in the real-time services.

Table 2. Summary of horizontal stability (standard deviations in millimeters) of SmartNet reference stations

	2017	2018	2019	2020	average
JED1	1	1.3	1.8	1.4	**1.4**
KIEL	1.2	1.5	1.4	1.3	**1.4**
SKAR	2.1	1.2	1.8	1.1	**1.6**
SZYD	1.2	1.4	1.1	1.1	**1.2**
average	**1.4**	**1.4**	**1.5**	**1.2**	**1.4**

Table 3. Summary of vertical stability (standard deviations in millimeters) of SmartNet reference stations

	2017	2018	2019	2020	average
JED1	3.3	4.4	3.6	3.7	**3.8**
KIEL	3.7	4.6	3.9	3.8	**4.0**
SKAR	3.8	4.5	3.9	3.7	**4.0**
SZYD	3.6	4.7	4.5	4.5	**4.3**
average	**3.6**	**4.6**	**4.0**	**3.9**	**4.0**

4.1 Station stability

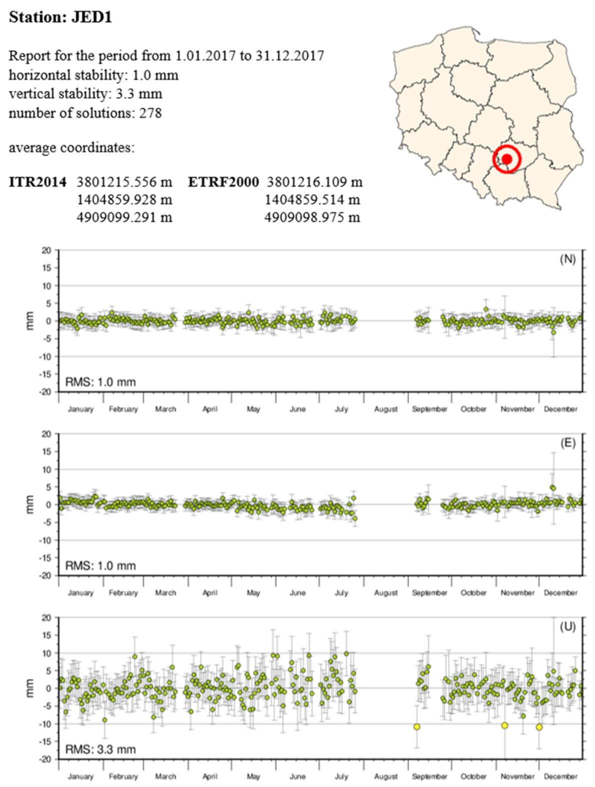
To analyze the stability of the stations used, data from (EPNACC WAT, 2023) sourced between 2017 to 2020 were considered. Stability was determined by comparing the current coordinates expressed in ITRS with those reported in real-time services for the following reference stations:

- JED1 – station in the town of Jędrzejów,
- KIEL – station in Kielce,
- SKAR – station in Skarżysko,
- SZYD – station in Szydłów.

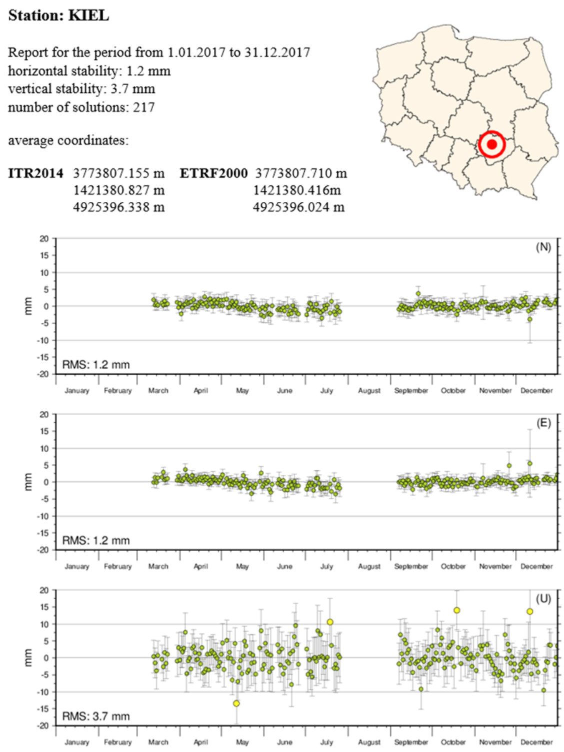
The stability data presented for the stations used (Figure 7) are mostly consistent. However, during the month of August, a significant break can be seen in all three coordinates. This is due to failures or upgrades to the station network system. This situation shows the necessity to analyze the measurement results for the determination of ground deformation in longer time series. It can also be seen that all four stations are twice as unstable between the X and Y coordinates and the Z coordinate (Tables 2 and 3).

4.2 Analysis of velocity models observed at reference stations

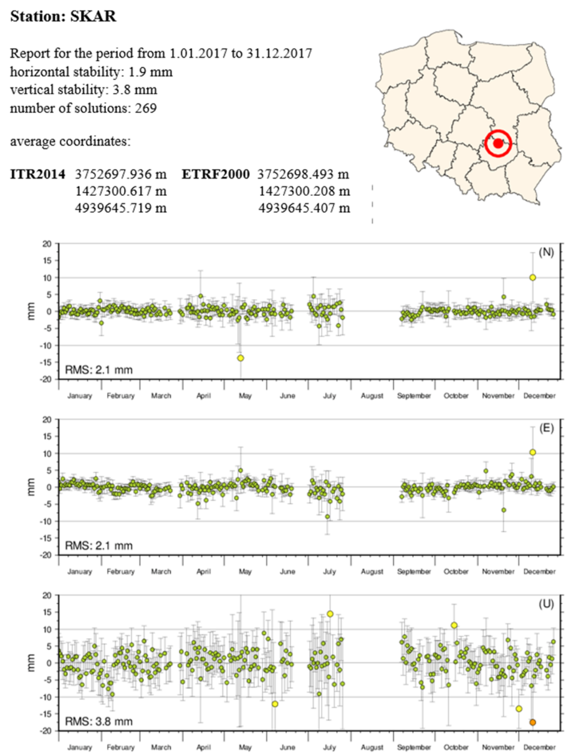
The increasing accuracy of GNSS measurement technology results in its regular use for monitoring tectonic movements and also for deformation of selected areas. The positions of each station for each day are determined to an accuracy of between 1 and 3 mm. From the changes in position over time, their average rates are determined, which we call station velocities. If two stations approach each other very slowly, then ideally we can speak of some deformation. In this way, we investigate the nature of the deformation rates (EPNACC WAT, 2023). It is now known that accurate 3-D determination of the position velocity of an observation station (reference point) requires a time series of coordinates over a period. With a smaller time series of, e.g. one year or six months, the results should be assessed simultaneously with the velocities. Also, the uncertainty of station coordinate changes may become too large to be defined as deformation or tectonic movement. Therefore, analysis of time-series



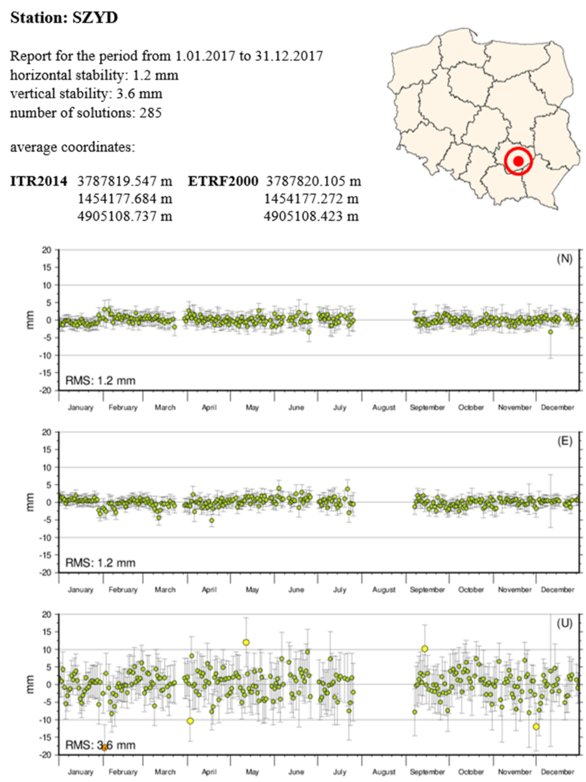
(a) JED1



(b) KIEL



(c) SKAR



(d) SZYD

Figure 7. Stability (standard deviation) of the JED1 (a), KIEL (b), SKAR (c) and SZYD (d) reference stations in 2017 (EPNACC WAT, 2023)

coordinates from GNSS observations is a prerequisite to obtain reliable velocities from a specific time series (Savchuk et al., 2020).

The presented velocity models were developed based on a cumulative solution from 2014-01-01 to 2021-10-30. Stations that had at least a 3-year observation period during the analyzed period were used to determine the velocity. The results of the analyzes are presented in the maps in the Figure 8. The two cartodiagrams show the so-called 'horizontal velocities' in the ITRF14 and ETRF2000 systems. One shows a homogeneous movement of the whole area in a north-easterly direction in the ITRF2014 system (Figure 8a). The second model shows velocities reduced by the movement of the Eurasiatic plate according to the ITRF2014 model (Figure 8b) and indicates movement in a westerly direction. The next map is a visualisation of the vertical movements by means of a cartodiagram (Figure 8c). The model shown predominantly indicates downslope.

A not dissimilar model presents smoothed velocities referenced to a stable part of Poland's region, the Eastern European Platform (Figure 9). This is the northern part of Poland, which is the most geologically stable not only in Poland but also in Europe. It therefore constitutes a stable reference system. Also, by applying filters and eliminating velocity anomalies of local character, a picture of velocities with tectonic features is obtained.

In the case of the region under study (Figure 9), it can be determined from the model presented that the horizontal velocities with respect to ETRF2000 are at 0.6 mm/year from the north and -0.53 mm/year from the east. The presented velocity models were developed based on the cumulative solution from 2014-01-01 to 2021-10-30. Stations that had at least a 3-year observation period during the analysed period were used to determine the velocity (EPNACC WAT, 2023). Therefore, more attention and a significant impact occur after 10 years or more. With multi-year monitoring of, for example, 20 years, velocity values can reach 11 mm in the eastern direction. This value will certainly be important when determining the coordinates of the control points.

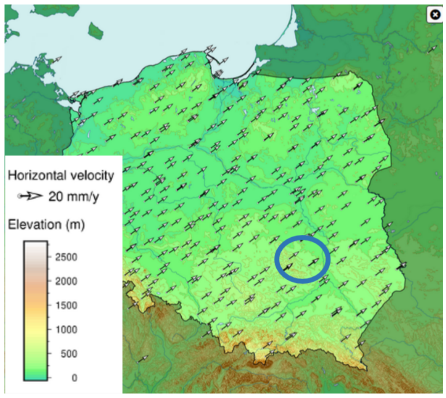
5 Criteria for the relevance of changes in the position of reference stations to the control points

Most reference stations are located on buildings where the horizon is stretched the most. Therefore, the displacement of the station can be caused by the movement of the ground or building on which it is installed. Additionally, ground movement can be a local landslide of sedimentary layers or result from a deformation of the whole geological structure. Therefore, it is important to correctly interpret the results of GPS measurements, as well as to measure stresses in the Earth's crust (Jarosiński et al., 2022).

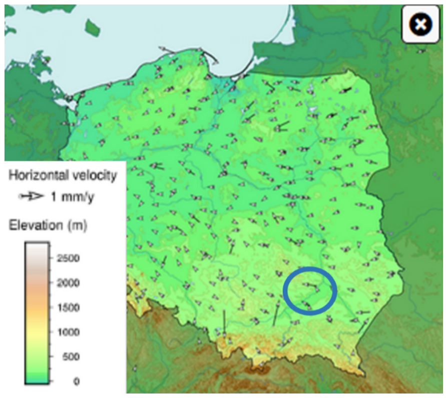
The coordinates in the ETRF2000 system of the reference stations (SmartNet) used for the control point at Kadzielnia were compared with the coordinates provided by real-time services (Figures 10 and 11). The presented graphs of coordinate comparisons from 2016 to 2022 show and detect a large change in the position of stations (Figure 11a) due to technical failures, which affects the change of station coordinates (e.g. the station in Kielce burned by a lightning strike). The analysis shows that the altitude coordinate was erroneously published in the network services of the reference station. The station coordinates were corrected after an interruption due to a failure in 2021 (Figure 11b). This means that the measurements of the altitude coordinate, which were based on this station between 2017 and 2021, were underestimated by 4 cm.

The summary table (Table 4.) for the period 2016–2022 shows an average deviation of station coordinates of 8 mm. The deviation values are significantly lower than the error values shown in Table 1 and will not have a major impact on the control points.

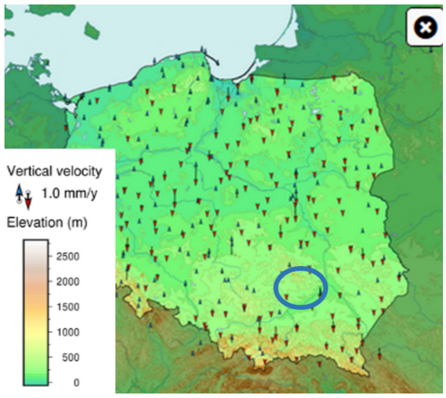
The interpretation of the results of the deformation observations also encounters another problem, namely: What magnitude of the deformation indices should be regarded as the actual change



(a) ITRF 2014 (EPNACC WAT, 2023)



(b) ETRF2000 (EPNACC WAT, 2023)



(c) vertical (EPNACC WAT, 2023)

Figure 8. Horizontal: ITRF 2014 (a), ETRF 2020 (b) and vertical (c) velocitites

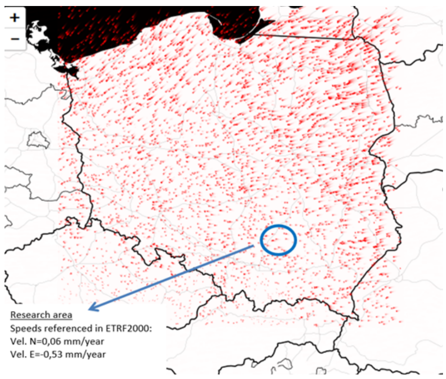


Figure 9. Horizontal velocities in the Świętokrzyskie region (EPNACC WAT, 2023)

Table 4. Summary of average deviations of station coordinates (2016-2022)

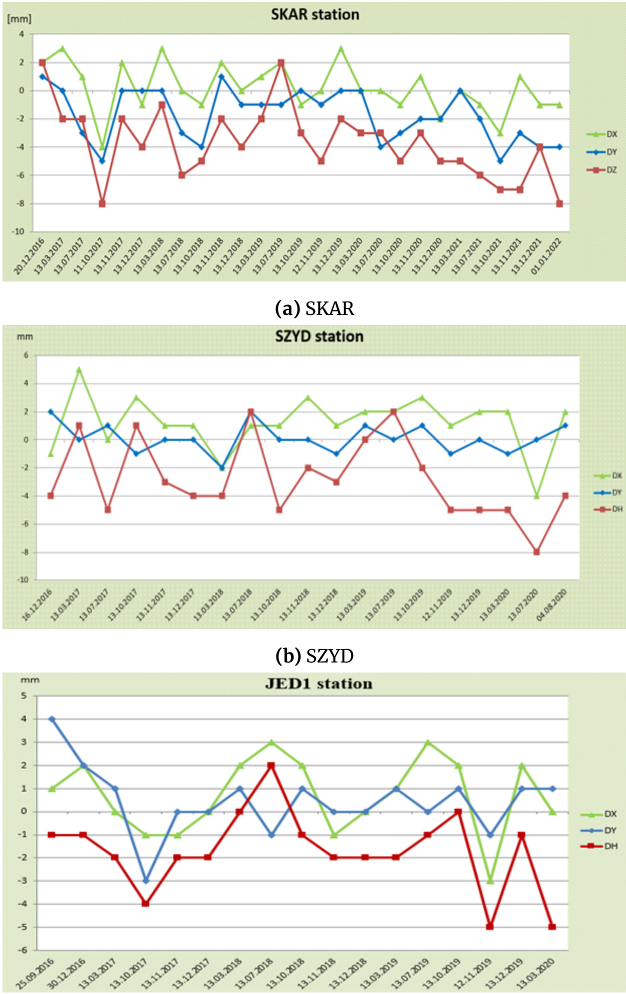
	2D [mm]	dh [mm]
SKAR	7,7	11,1
SZYD	6,5	8,4
JED1	5,6	5,1
KIEL	13	–
average	8	8

Table 5. Boundary errors in determining the position of the station (2016-2022)

	2D [mm]	dh [mm]
SKAR	2,6	3,7
SZYD	2,2	2,8
JED1	1,9	1,7
KIEL	4,5	–
average	3	3

Table 6. Boundary errors in determining the position of the control point

Year	errors value [mm]	
	2D	m_H
2014	42	60
2014	36	57
2014	30	63
2015	9	51
2016	30	63
2019	30	33
average	29	55

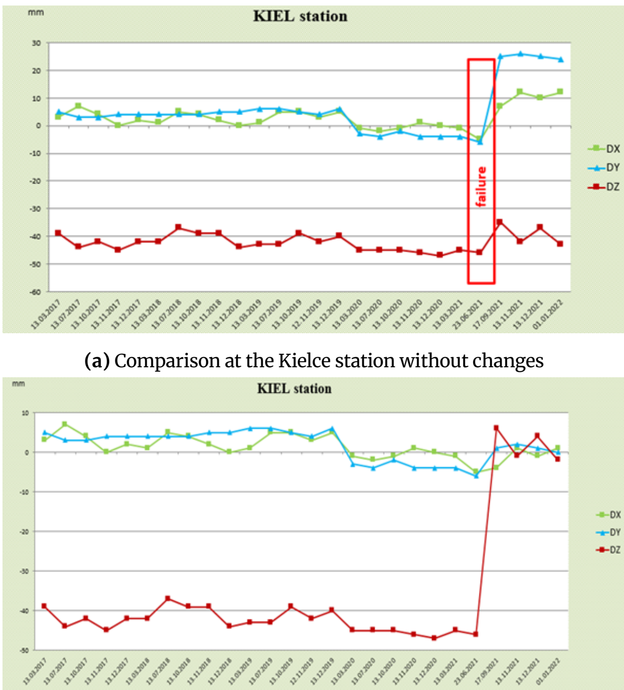


(a) SKAR

(b) SZYD

(c) JED1

Figure 10. Comparison at the SKAR (a), SZYD (b) and JED1 (c) stations



(a) Comparison at the Kielce station without changes

(b) Comparison at the Kielce station after correction of coordinates

Figure 11. Comparison at the Kielce station without changes (a) and after correction of coordinates (b)

in the ground surface and what is the result of the measurement errors made. As already mentioned, the basic way to solve this problem is to determine, on the basis of independent measurements, the observation error and to carry out a study of the constancy of the control points, as a result of which a possible correction of the coordinates of the control points may take place.

The study of the significance of changes in the control points, shown from the comparison of coordinates between coordinates in the ETRF2000 system of the reference station and coordinates given in real-time services, requires the definition of a criterion above which a change is considered significant (not caused by observation errors). Usually, this criterion is taken to be the limiting error, which is 2 or 3 times the mean error of the observations:

$$g = (2 \div 3)\, m_{mean}$$

Adoption of the first coefficient implies a probability of error less than the limiting error of 95%; the second magnitude implies a probability of 99.9% (as is known, the probability of error less than the mean error is 68%) (Krawczyk, 2021).

Table 1 specifies the average errors in values to determine the position of the warp points in individual years, on the basis of which the boundary errors were determined (Table 6). For the determination of the limiting error, a coefficient of 3 was adopted in relation to the mean error. The probability of occurrence of a value greater than the limiting error is then – as indicated above – 1%; in the author's opinion, this issue concerns the most important element, the control points, and therefore almost 100% certainty is needed for determining any changes. This criterion is very important as it affects the early warning process. After rounding the values and multiplying by $\sqrt{3}$, according to the law of error propagation, the following criterion values are obtained for changes in the positions of the points (Table 6).

The limit errors of the position determination of the used stations are on average 8 mm (Table 5), and for the control points 29 mm for the plane coordinates and 55 mm for the height coordinate (Table 6).

6 Conclusions

1) The significance criteria for the magnitude of the deformation were established according to the 3σ rule obtaining:
   a) the change in plane coordinates due to the determination of the point position:
      - for static measurement x,y rounded: 29 mm,
      - for static measurement height: 55 mm;
   b) the change of plane coordinates due to determination of station position:
      - for x, y measurement rounded off: 8 mm,
      - for height measurement: 8 mm.
2) The demonstrated stability of the stations used has little effect on the determined position of the control point. Station errors are considerably smaller than the errors in determining the coordinates of the control point. The presented results of the research confirm the concordance with research (Figurski et al., 2010), which state that national GNSS networks can realise a stability reference system for the whole region for various precise geodetic and geodynamic measurements.
3) Using stations as reference points to test the stability of the control points requires referencing to several stations. The presented graphs of coordinate comparisons in the ETRF2000 system with coordinates given in real-time services in the years 2016-2022 show and detect a large change in the position of stations due to technical failures, which affects the change of station coordinates (e.g., burned station in Kielce by lightning strike).
4) Demonstrated velocities in the study area of 0.6 mm/year from north and east -0.53 mm/year, will have an impact on real-time coordinates over a longer time period (20-year – 11mm).
5) Interference with GNSS signals may occur during the prevailing war in Ukraine. This directly affects the determination of the coordinates of the control points. Therefore, one should not forget to include classical methods when investigating the constancy of the control point, such as, for example, precision levelling or angular-linear measurements. It is worthwhile taking precautions during this period by supplementing the control point with additional points outside the zone of influence.

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