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Research paper

Influence of ground moisture on GNSS-observed benchmark displacements in Wrocław city center, SW Poland

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Abstract: In the context of the most accurate measurement of the displacements of engineering objects, a preliminary correlation was made between GNSS measurements and changes in ground humidity. GNSS measurements were made in the center of Wrocław on four benchmarks at important existing investments. The influence of the geological structure of the investment area was analyzed, which corresponded to changes in humidity and the displacements of benchmarks. It turned out that there is a preliminary correlation between benchmarks located in geologically unstable areas and the humidity of these areas. It results not only from statistical analyses, which was presented in the previous article. The correlation of displacement values with respect to the change in moisture content of cohesive soils such as clays has been shown. This can improve the accuracy of measurements of displacements of engineering structures located on cohesive and organic soils. Then, changes in the temperature of the soil medium also occur. This relationship requires more detailed investigation.

Keywords: humidity measurements, GNSS measurements, deformations of engineering objects, vertical displacements, Wrocław city center

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1. Introduction

The aim of this work is to demonstrate a preliminary correlation between the displacement values of organic soils, such as silts, which release water under pressure, and GNSS satellite measurements of these displacements. Further correlation will allow for the detection of precise values of these changes, which will, over time, improve measurement accuracy to 0.1–0.01 mm. Wroclaw is a region where many important construction projects are located on islands composed of organic soils, which can shift very slowly (0.01–0.1 mm per year) due to pressure from structures and water loss. In the case of peat, which does not occur here, such movements can reach several cm per year. The measurements of the displacements of engineering structures using levelling techniques were performed by various researchers in Poland and abroad. They included Prof. Stanisław Pachuta and Prof. Kazimierz Thiel (1968), who studied the displacements within dams. The settlements of elevators, bridges and industrial structures were also measured. The development of GPS satellite techniques [1] was used by a team of researchers from the University of Environmental and Life Sciences in Wrocław on local geodynamic polygons in the Sudetes and the Fore-Sudetic block in the eighties and nineties of the last century [2]. The integration of satellite and levelling techniques proved effective in tectonically active, faulted areas (with a complex deep geological structure) by recording the displacements of rock blocks in both the Table Mountains and the Bear Cave. GNSS satellite techniques were used to monitor the displacements of drilling platforms [3] and the displacements of dams [4]. The geological structure of the terrain was an element that played a significant factor in integrated measurements of landslide displacements [5]. In Wroclaw, since the 1960s, intensive development of housing estates and industrial facilities has been carried out. Many important construction investments are located within islands built of organic soils. Therefore, existing and planned facilities in this area may be subject to cracks and displacement of structural fragments.

Reliable monitoring of deformations of existing and planned engineering facilities in Wroclaw justified the implementation of an appropriate control and measurement system consisting of benchmarks located in geologically stable areas and unstable areas [6]. The basic fundamental network is made up of points designated in networks of the highest accuracy, which transfer the geodetic reference system and the height system to the country. The basic base network is made up of points designated in networks of the highest accuracy, which implement the adopted reference systems and which are evenly distributed across Poland. Detailed control network – these are points designated in networks that are an extension of the basic geodetic control network, and their density depends on the degree of urbanization of the area. Measurements using a control and measurement system were referred to the detailed control network points. Subsidence processes caused by unstable geological structure of organic and cohesive soils – clays, silts [7] can cause deformation of the ground surface in an area that significantly exceeds local measurements. Therefore, reference points previously considered stable can also be subject to displacement. In order to observe correlations between millimeter values of displacements and percentage changes in humidity, GNSS satellite measurements were performed in close correlation with humidity changes at a depth of 30 cm – PCE-SMM1 hygrometer. The measurements will be a prelude to thermal measurements using the Opotsky spectrophotoradiometer.

The innovative nature of this article lies in demonstrating a preliminary correlation between GNSS satellite measurements and changes in soil moisture to improve the accuracy of displacement measurements of strategic engineering structures located on geological formations that exhibit very small annual displacements of the order of tenths of a millimeter. This correlation will later allow for the additional consideration of statistical factors and genetic algorithms in the creation of a comprehensive algorithm enabling the measurement of displacements of strategic engineering structures with very high accuracy of the order of 0.01–0.1 mm. Strategic engineering structures from the perspective of the government include natural gas reservoirs located in salt formations, large hydroelectric power plants, and wind farms located on seemingly stable formations that may be subject to displacement under the influence of water pressure and climate change.

2. Experiment

2.1. Materials and geology of the area

GNSS satellite measurements were taken on four earth benchmarks listed in Table 1. They were performed on March 12 and March 22, 2025. They lasted three hours. These benchmarks are located on cohesive clay soils with properties similar to water-repellent alluvial soils and stable sand and gravel soils. Simultaneously, twice daily, on March 12 and 22, moisture changes were measured next to each benchmark. Moisture measurements were taken before and after the GNSS measurements. The table below were selected from the benchmark locations below, previously measured using the control and measurement system. The first column contains the catalog number (Table 1).

When examining the stability of the reference benchmarks, changes in height differences between them over time were analysed. A stable geological substrate causes height changes, if any, to be very small. In an unstable area composed of peat and alluvial deposits, significant displacement of benchmarks occurs. For five reference benchmarks, there are ten possible pairs of benchmarks (combinations of connections between benchmarks). Eight connections come from direct measurement, and two were obtained by calculation (pair 1074–1020 and pair 1074–1029) by searching for the shortest connection using measured leveling sections. The general outline of the geological structure in the immediate vicinity of benchmark no. 4 is presented in They are cohesive soils. Under the influence of wetting, they change their volume and also the fill with diverse lithological properties, susceptible to moi1sture changes. In Fig. 2, there are no clays. The area of benchmarks 1, 2 and 3 is therefore more stable geologically.

As cohesive soils or drain water under pressure give up water, both moisture content and temperature change. This causes displacements that can be captured using GNSS. Is caused by the correlation between satellite measurements of displacements and soil moisture. These changes can affect the type and nature of displacements. In this case, soils with properties similar to organic soils are clays (Fig. 1).

The area of benchmarks 1, 2 and 3 is therefore more stable geologically (Fig. 2).

Numerical values of the scales on Figs. 1 and 2 is depth from sea level and thickness of geological layer of ground sediments. It was important that during the performance of two

Table 1. List of adopted reference benchmarks

No	Height [m]	mH [mm]	Localisation
334 **1073**	119.29057	0.04	Wrocław – Old Town, ul. Krupnicza 15, corner of ul. P. Włodkowica, Sports Hall; front wall of the building
334 **1074**	117.95602	0.06	Wrocław – Old Town, Podwale Street 28/29, corner of Sądowa Street, Provincial Court; central retaining pillar
334 **1305**	118.49016	0.05	Wrocław – Old Town, 1 Podwale St., corner of Muzealna St., Provincial Prosecutor's Office; front wall of the building, rounded corner
343 **1020**	118.54805	0.07	Wrocław – Old Town, ul. K. Wielkiego 3, corner of ul. S. Leszczyńskiego, "SPOŁEM" Consumer Cooperative – North Branch; southern wall of the building
343 **1029**	119.50775	0.05	Wrocław – Old Town, ul. Swidnicka 35, corner of ul. H. Modrzejewska, State Opera; front wall of the building

subsequent measurements at a given position, the same tripod with the receiver was present. The accuracy of these measurements is 1 mm/km in the case of class I precision levelling lines and 2 mm/km in the case of class 2 precision levelling lines [8]. The purpose of the precise levelling was to determine the height of the benchmarks located in the immediate vicinity of the observation stations [9]. The levelling was performed from the benchmark considered stable to the benchmark at stations 1, 2, 3, 4 and in the return direction. During the own measurement, the GPS receivers were mounted on tripods screwed into the ground. The measurement time was 3 hours. The measurement was performed with reference to geologically stable benchmarks and the nearest reference stations. This improved the accuracy of the vertical and horizontal coordinate errors. Levelling was performed in two directions from a benchmark deemed stable to the station and back. Accuracy estimated based on double measurement is 0.1 mm. The measurements were performed in the PL-EVRF 2007 system. In order to verify and check the stability of the height of the benchmarks at the stations in the vicinity of the benchmarks considered stable and the benchmark located at the station in the immediate vicinity of the EcoGenerator Plant, GNSS-GPS satellite measurements were performed using 4 Trimble R2 receivers (Fig. 3).

The stability of the reference stations over time has been increased by referencing the geologically stable benchmarks. Information about kinematic measurements has been removed.

The first measurement performed in March 2025 lasted 6 hours, the second measurement at the end of March 2025 – 3 hours. The coordinates x and y were determined in the PL-ETRF system, while the height coordinates were determined in the PL-EVRF 2007 system. In summary, the GNSS satellite methods were performed using four receivers and were taken between two moisture measurements. Both measurement methods have been used independently and presented in numerous geodetic and geological publications.

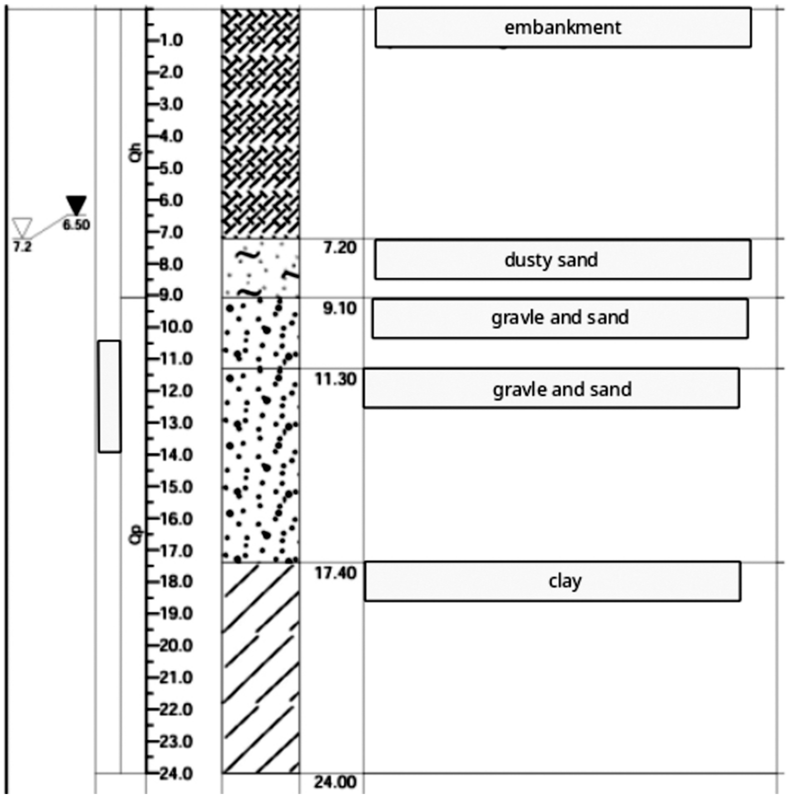

Fig. 1. Geological structure of the discussed area for benchmark no. 4 (own study)

2.2. GNSS measurement method and soil moisture preparation method

Measurements was done on first 4 points from Table 1. Determination of horizontal coordinate components of points based on GPS satellite observations is currently performed with millimeter accuracy. Such accuracy is obtained for global networks (e.g. IGS), regional networks (e.g. EPN), and local networks, and these are most often results from repeatable 24-hour sessions [10]. The postprocessing settings used precise ephemerides and included an ionosphere model. The alignment was performed using the least squares method [11, 12]. As a result of measurements linked to a geodetic control point with known coordinates (Legnica, Walbrzych, Opole stations), coordinate increments [m] were obtained between this point and two new points 2 and 3, as well as error matrices of increments [mm]. The observation equations of triple phase differences are formulated assuming one of the satellites as the base. For example, for four available satellites, 3 equations are formulated (combinations 1–2, 1–3, 1–4) containing three unknown corrections dX, dY, dZ to the approximate coordinates of the rover X_B, Y_B, Z_B. The full observation system contains a multiple of these equations, for each pair of measurement moments t_1, t_2. As a result of its solution by the least squares method, the

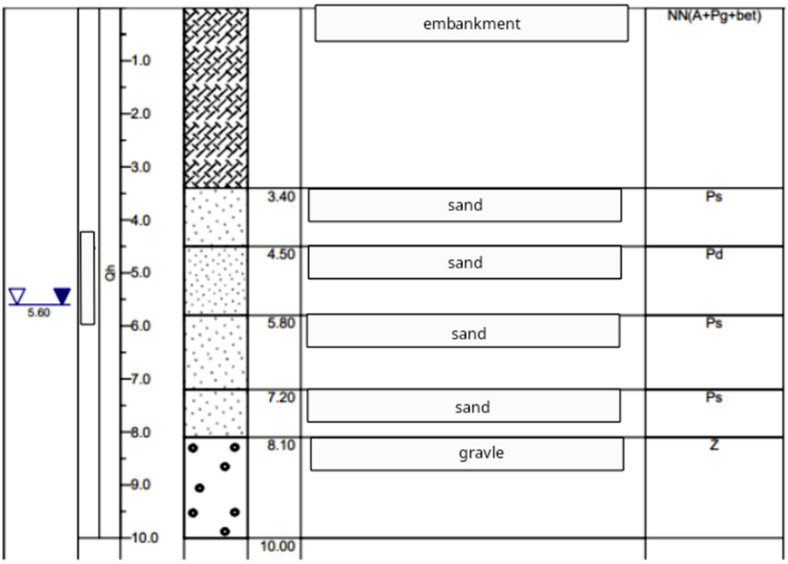

Fig. 2. Geological structure of the benchmark area 1–3. The lack of clays shows the stability of the area (own study)

Fig. 3. Trimble R2 receiver (website www.geotronics.com.pl)

corrections dX, dY, dZ and the coordinates of the rover $X_B + dX$, $Y_B + dY$, $Z_B + dZ$ are obtained with a mean error of the order of 0.05 m. The observation equations of double phase differences are formulated analogously to triple phase differences, assuming one of the satellites as the base. The mean errors of the corrected coordinates are of the order of 0.05 m. The corrections dX, dY, dZ to the approximate coordinates of the rover X_B, Y_B, Z_B, assuming known, constant values of the number of cycles determined in the first double phase difference adjustment, are determined by resolving the double phase difference equations. Mean errors of the order of 0.005 m. We obtain the correction error matrix.

This matrix is also the matrix of coordinate increment errors:

$$\Delta X = X_B - X_A,\ \Delta Y = Y_B - Y_A\ \Delta Z = Z_B - Z_A \tag{2.1}$$

On this basis, the error of the determined point B relative to the reference point A:

$$m_B = \sqrt{m^2_{\Delta X} + m^2_{\Delta Y} + m^2_{\Delta Z}} = \sqrt{m^2_{dX} + m^2_{dY} + m^2_{dZ}} \tag{2.2}$$

As a result of measurements linked to the geodetic control point and with known coordinates, coordinate increments [m] are obtained between this point and two new points 2 and 3 and error matrices of increments [mm^2]. Observations were linked to the three closest reference stations – Legnica, Walbrzych, Opole – variant I and Opole, Walbrzych, Kepno – variant II.

PCE-SMM 1 soil moisture meter: Measuring device for determining soil moisture / with a 250 mm probe / measuring range up to 50% / waterproof. The amount of water in the soil plays an important role in many areas of agriculture, horticulture and environmental protection. Because moisture in the soil allows for drawing conclusions regarding, among others, the behavior, fertility and water storage capacity. The PCE Instruments soil moisture meter with a 250 millimeter probe has been specially developed for quick, easy and precise determination of soil moisture. The user-friendly soil moisture meter reliably displays the water content in the soil from 0 to 50 percent with a resolution of 0.1 percent. Using the soil moisture meter is simple and effective. After inserting the sensor with the two-pole moisture electrode into the housing, the probe can be attached by tightening the ring. After removing the protective cap from the sensor head, the soil moisture meter is ready for use. To determine the water content in the soil, the soil moisture meter probe is inserted to a depth of at least ten centimeters. The measurement results are then quickly and clearly displayed on the large LCD display of the soil moisture meter. The manufacturer has equipped the soil moisture meter with a practical data logging function that records the minimum and maximum measured values. The compact dimensions and battery operation enable mobile use of the soil moisture meter, while the stable and waterproof plastic housing protects the internal components even under difficult operating conditions. So that the battery-powered soil moisture meter is always ready for use, it gives early warning when the batteries need to be replaced. The soil moisture meter can be used in a temperature range of 0 to 50 degrees Celsius and at a humidity of up to 80 percent [13]. The glass prism of the digital Brix refractometer, which is enclosed in a stainless steel cavity, can be quickly and easily cleaned before and after measurement and is sealed with a plastic prism cover. The manufacturer has designed the Brix refractometer in such a way that the glass prism is protected from damage. Convenient operation with three buttons guarantees easy operation. In order to save the battery of the measuring device, the manufacturer has equipped the digital Brix refractometer with an automatic switch-off function. If the Brix refractometer is not used, it switches off automatically after one minute. If necessary, a few drops of distilled water are enough to calibrate the Brix refractometer yourself at the touch of a button. Areas of application: The soil moisture meter guarantees maximum reliability and precision. With the soil moisture meter, you can quickly and easily determine the water content in the soil. The soil moisture meter is therefore ideal for reliable immediate analyses in agriculture, horticulture and environmental protection, is versatile and easy to use. The waterproof housing allows easy cleaning and use in all weather conditions.

Thanks to the handy and robust design and battery operation, the soil moisture meter can be used anytime and anywhere. Its simple operation makes the soil moisture meter indispensable when checking the soil and is also suitable for inexperienced users [14]. Soil, organic and cohesive soil is completely saturated with water when all the pores in the soil are filled with water. Under the influence of gravity, some of the water seeps into the deeper layers of the soil. This vertically moving water is also known as seepage and ultimately becomes groundwater. Soil moisture or water bound to the surface by surface tension and capillary forces is not groundwater and is therefore also referred to as retained water. Soil moisture is divided into five moisture classes (wet, moist, fresh, dry, dry). The important factors determining the water absorption or storage capacity of the subsurface layers are the pore size and density of the soil, as they determine the water retention capacity. Moisture changes were observed every 10 days for a month during March 2025 and at the beginning and at the end of each measurement session on March 12 and 22. Its significant changes could be observed between March 12 and 22. The alignment of observation results to the Kepno station in the 3-hour interval gave similar accuracies for errors of mean vertical displacements than the alignment of observations to the Legnica station in the same interval. In the 6-hour and 1-hour intervals, the results of the alignment of observation results to the Kepno station for errors of vertical displacements gave similar accuracies compared to the alignment to the Legnica station, while for horizontal coordinates they were less accurate.

3. Results and discussion

Precise levelling [15] immediately preceded the first GNSS satellite measurement. The first satellite measurement was performed in 12 March 2025, the second in the second half of March 2025–22 March. The time of commencement of measurements and the interval between measurement sessions, which was 10 days, were important. The alignment of GNSS-GPS satellite measurements of the benchmark located in the immediate vicinity of the EcoGenerator Plant and the benchmarks of the first segment of the system was performed both in relation to the nearest reference stations ASGEUPOS -Legnica, Walbrzych, Opole and one reference station ASGEUPOS – Kepno (Variant II). Within a month, benchmark No. 4 was displaced by 1.4 mm, which confirms the instability of the terrain of the Odra Islands. Benchmarks 1–3 show stability. The second GNSS-GPS satellite measurement was performed on March 22, 2025. The satellite network included 4 points in Wroclaw area. 3-hour observations gave similar measurement accuracy as 6-hour observations of the first measurement session. In both observations, the interval was 1 second. The antenna height was measured using a rigid ruler with a millimeter division. Observations in individual sessions were independent vectors. As a result of the study, coordinates were obtained in the PL-ETRF 2000 rectangular flat coordinate system and the PL-EVRF 2007 altitude coordinate system. As part of our own research, an analysis of changes in the height of the benchmarks was carried out. The analysis of changes in the length of the vectors did not show horizontal displacements. Based on the observation results, the stability of benchmarks 1, 2, and 3 was found. Benchmark 4 showed significant vertical displacements caused by the settlement of organic soil (peat) – 1.4 mm in half a year (Table 3 and 5). This means that the frequency of measurements every six months is appropriate for monitoring ground displacements in the immediate vicinity of planned and existing engineering structures on the Odra Islands. The mean error of displacement values with known mean errors (3.1) for coordinates x, y and z was also calculated (Table 3 and 5).

$$m_u = \sqrt{m_{x1}^2 + m_{x2}^2} \tag{3.1}$$

Option I (Legnica, Walbrzych, Opole stations).

Corrected values of vertical and height coordinate errors. This was possible by relating GNSS measurements on benchmarks to geologically stable areas (Table 2).

Table 2. I and II measurements – March 12 and March 22, 2025 (3 h interval)

Position	**Coordinate *X* (error mm)**	**Coordinate *Y* (error mm)**	**Height H (error mm)**
Measurement on 12 March			
1	1.0	1.2	5.3
2	1.6	1.0	4.7
3	1.8	1.3	6.4
4	1.1	0.7	4.3
Measurement on 22 March			
1	1.4	1.1	5.3
2	1.8	1.4	5.1
3	1.7	1.3	7.2
4	1.2	0.9	4.6

By comparing the same measurement intervals, the vertical displacements of benchmarks as well as the errors of the mean displacements were calculated (9). The height difference between the first and second GNSS measurements was calculated (Table 3).

The values of the mean errors for horizontal displacements that were not observed are:

– after x benchmark 1 ± 1.7 mm,
– after x benchmark 2 ± 2.4 mm,
– after x benchmark 3 ± 2.5 mm,
– after x benchmark 4 ± 1.6 mm,
– after y benchmark 1 ± 1.4 mm,
– after y benchmark 2 ± 1.7 mm,
– after y benchmark 3 ± 1.7 mm,
– after y benchmark 4 ± 1.1 mm.

Option II (stations Opole, Walbrzych, Kepno).

Advantage of the second reference variant to the additional reference station Kepno. This increased the accuracy of determining horizontal and height coordinate errors even more, which enabled reference to humidity changes and the capture of preliminary correlation (Table 4).

Vertical displacement of benchmarks are presented in (Table 5).

Table 3. Benchmarks displacements

No point	**Displacement of point ΔH_z [mm]**	**Mean error displacement $\pm m_{\Delta Hz}$ [mm]**
1	0	7.5
2	0	6.9
3	0	9.6
4	–1.4	6.2

Table 4. I and II measurements – March 12 and March 22, 2025 (3-hour interval)

Position	**Coordinate *X* (error mm)**	**Coordinate *Y* (error mm)**	**Height *H* (error mm)**
Measurement on 12 March			
1	1.6	1.1	5.3
2	2.2	1.2	3.2
3	1.4	1.2	4.8
4	1.3	1.1	2.2
Measurement on 12 March			
1	1.5	1.1	5.3
2	2.1	1.5	3.5
3	1.6	1.3	5.0
4	1.4	1.1	2.7

Table 5. Vertical displacement of benchmarks

No point	**Displacement of point ΔH_z[mm]**	**Mean error displacement $\pm m_{\Delta Hz}$[mm]**
1	0	7.4
2	0	4.7
3	0	6.8
4	–1.4	3.5

The measurement results were reduced to the common reference system PL-ETRF 2000 and PL-EVRF 2007, which confirms the validity of using stable benchmarks as reference points of the first segment of the control and measurement system. Stable benchmarks therefore enable observations in 3D space, although due to the detection of only vertical displacements, the control and measurement system for conducting observations in 1 D space seems more justified. They are additional control points for the nearest reference stations. The heights of the remaining benchmarks in the I and II class lines, which are equalized in relation to them, allow for improving the accuracy of the alignment of the entire system in relation to the nearest reference stations, which gives millimeter measurement accuracy. If we wanted to conduct observations in 3D space, we could replace the stable benchmarks with the nearest reference stations (Opole, Walbrzych, Kepno). The current alignment in relation to the nearest reference stations was justified due to the comparison of observation intervals (1, 3 and 6 hours). The most optimal observation interval was 3 hours. The accuracies of the obtained coordinates and their errors in the 3-hour and 6-hour interval were similar. Horizontal coordinate errors ranged from 1.0–2.1 mm, while in the 1-hour interval they were 1.6–2.9 mm. Vertical coordinate errors in two measurements in the 3-hour interval were 2.2–5.3 mm, while in the 1-hour interval they were 6.4-9.3 mm. Geocentric coordinates and deviation values for individual measurements are presented in attachments (adjustment reports) generated using the Trimble Business Centre software.

Two levels of abstraction are used in the definitions of latitude and longitude. In the first step, the physical surface is modeled by the geoid, a surface that approximates the mean sea level over the oceans and its continuation under the land masses. The second step is to approximate the geoid by a mathematically simpler reference surface. The simplest choice for the reference surface is a sphere, but the geoid is more accurately modeled by an ellipsoid.

Geocentric latitude (also called spherical latitude, from the 3D polar angle): the angle between a radius (from the center to a point on the surface) and the equatorial plane. There is no standard notation: examples from various texts include θ, ψ, q, $\phi\prime$, ϕ_c, ϕ_g. A summary of geodetic coordinates, ECEF coordinates, and error components and covariance terms for similar measurement is shown in (Table 6).

Table 6. ECEF, ellipse error components and covariance terms for the first GPS measurement

Name of observation	Data	Observation
3 → 2 (PV352)	Az.	261°52’43.8"
	Δheigh.	–7.6719 m
	ellipsoidal distance	9967.1293 m
3 → 4 (PV357)	Az.	306°13’11.9"
	Δheigh.	–7.6672 m
	ellipsoidal distance	11029.7145 m
4 → 2 (PV328)	Az.	186°51’45.4"
	Δheigh.	–0.0048 m
	ellipsoidal distance	7984.3395 m
4 → 3 (PV360)	Az.	296°41’31.4"

Humidity was measured at the beginning and at the end of each measurement session on March 12 and 22. Measured humidity changes were:

March 12, 2025 – P.1 12%. P.2 10% P.3 14% P.4 21% beginning of measurement, March 22, 2025 – P.1 11%. P.2 10% P.3 14% P.4 15% beginning of measurement, March 12, 2025 – P.1 12%. P.2 10% P.3 14% P.4 10% ending of measurement, March 22, 2025 – P.1 11%. P.2 9% P.3 15% P.4 4% ending of measurement.

The soil moisture increased in dry seasons in March when, under the influence of the pressure of engineering structures, silts and clays gave up water. Their temperature decreased then. When the water level dropped, displacements occurred. A clear correlation is visible for point four, which, according to GNSS measurements, was subject to displacements, while its moisture decreased from 10 percent to 4 percent between 12 and 22.

The implemented method of geodetic examination of surface deformation of clay sediments [16] and engineering structures [17] in the area of Wroclaw is a "tool" for providing reliable results on their safety status. The flat terrain of the city justified the creation of a two-segment control and measurement system for monitoring deformations in 1D space [18]. An appropriate procedure for comparing changes in the height of benchmarks and stable geological subsoil provided the basis for selecting the location of these points [19, 20]. This stage of work has been completed. Stable reference benchmarks due to the lack of displacements over long periods of time (25 years) and equalized heights of benchmarks. The recorded values of vertical displacements in the area of benchmark no. 4, reaching up to –1.4 mm within ten days. The 3-hour measurement interval provides the greatest accuracy and limits the time of performing GNSS measurements [21].

4. Conclusions

The measurements taken in Wroclaw to record the deformation of the above-mentioned objects are secured by the spatial factor (reference system) of this and the new, planned objects. Unfortunately, the start time of the deformation studies of the existing structure is late.

The millimeter accuracy of determining displacements in relation to stable benchmarks allows for the analysis of other phenomena related to movements in the near-surface layer of the earth's crust.

The heights of the remaining benchmarks, equalized in relation to stable benchmarks and the nearest reference stations, will constitute the basis for the modernization of the elevation network in the area of the city of Wroclaw.

The values of errors of the average horizontal displacements within the range of 1–2 mm and vertical displacements 2.8–5 mm in the 3-hour observation interval confirm the accuracy assumptions adopted to capture the correlation between humidity changes and vertical displacements of the benchmarks:

– humidity changes March 12, 2025 – P.1 12%. P.2 10% P.3 14% P4 21% beginning of measurement,
– humidity changes March 22, 2025 – P.1 11%. P.2 10% P.3 14% P4 15% beginning of measurement,
– humidity changes March 12, 2025 – P.1 12%. P.2 10% P.3 14% P4 10% ending of measurement,
– humidity changes March 22, 2025 – P.1 11%. P.2 9% P.3 15% P4 4% ending of measurement.

They show a clear correlation at point 4 with the displacements of the benchmark. High accuracy of determining vertical displacements of salt in relation to stable benchmarks and the nearest reference stations will be important when selecting places within salt structures for the construction of UGS (underground gas storage facilities), showing salt displacements of up to 0.1–1 mm/year, which can lead to the formation of voids within their cover. This is an investment of strategic importance.

The research results will constitute the basis for the construction and conducting reliable monitoring of deformation of both planned and existing facilities.

This relationship requires more detailed investigation.

The next step in the research will be to perform statistical analyses using multiple regression and to construct a genetic algorithm also based on properties such as changes in soil moisture and temperature.

The main limitations of the conducted research are the appropriate weather conditions and the proper organization of GNSS-GPS satellite measurements. These measurements require repeatability at regular intervals, which impacts their quality and accuracy. Humidity changes can also be caused by factors other than the geological properties of the ground. However, these changes are not significant or sudden.

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Poprawa dokładności pomiarów przemieszczeń reperów w centrum Wrocławia poprzez korelację pomiarów GNSS i wilgotności gruntu, SW Polska

Słowa kluczowe: pomiary wilgotności, pomiary GNSS, deformacje obiektów inżynierskich, przemieszczenia pionowe, centrum Wrocławia

Streszczenie:

W kontekście jak najdokładniejszego pomiaru przemieszczeń obiektów inżynierskich, dokonano wstępnej korelacji pomiędzy pomiarami GNSS a zmianami wilgotności gruntu. Pomiary GNSS wykonano w centrum Wrocławia na czterech reperach przy ważnych istniejących inwestycjach. Przeanalizowano wpływ budowy geologicznej terenu inwestycji, która odpowiadała zmianom wilgotności i przemieszczeniom reperów. Okazało się, że istnieje wstępna korelacja pomiędzy reperami zlokalizowanymi na terenach niestabilnych geologicznie a wilgotnością tych terenów. Wynika to nie tylko z analiz statystycznych, które przedstawiono w poprzednim artykule. Wykazano korelację wartości przemieszczeń względem zmiany wilgotności gruntów spoistych, takich jak gliny. Może to poprawić dokładność pomiarów przemieszczeń obiektów inżynierskich zlokalizowanych na gruntach spoistych i organicznych. Wówczas występują również zmiany temperatury ośrodka gruntowego. Zależność ta wymaga bardziej szczegółowych badań.

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