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The Three-Segment Control and Measurement of Reliable Monitoring of the Deformation of the Rock Mass Surface and Engineering Structures on the Międzyodrze Islands in Szczecin, NW Poland

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Abstract: The research area is located in north-western Poland. It is the city of Szczecin with a particular emphasis on the Międzyodrze islands. The area of the EcoGenerator Waste Disposal Plant is part of the research area. The analysis of the geological structure of the subsurface layer of Earth's crust within Szczecin, was carried out with particular emphasis on the EcoGenerator Waste Disposal Plant. The analysis of height changes of the benchmarks, was based on archival materials measured in two campaigns. A detailed recognition of the geological structure in connection with the analysis of changes in the height of the benchmarks was important. This enabled stable benchmarks to be located in several areas of Szczecin. They formed the basis for reliable monitoring of surface deformations of organic and existing sediments within the EkoGenerator Plant. The application of an appropriate three segment control and measurement system. In the area around the EcoGenerator Plant, vertical movements of the area were observed using the InSAR Small Baseline Subset Method. An InSAR analysis is only used here for very broad identification of the moving area. The radar data came from Sentinel 1 A and 1 B satellites. A total of 129 images from 15.11.2014 to 28.07.2019 were used.The results of the analyses conducted, form the basis for discussion and act as a summary of the considerations in this paper.

Keywords: organic deposits; organic soils; Międzyodrze islands; precision levelling; vertical movements; deformation monitoring; InSAR Small Baseline Subset Method

1. Introduction

As a port city, Szczecin is an important communication centre. The economic structure of the city is diverse by port development. It has been shaped and is progressing towards maritime economy development. The main industries are shipyards, steelworks, paper mills, as well as seaports. Most of these are located in the vicinity of the Międzyodrze islands. The influence of the industrial infrastructure has also become apparent within the Odra islands [1]. During the last century, deformation measurements of many engineering facilities were not carried out. Subsoil instability became apparent in the form of cracks and settlements of buildings on islands, which are geologically unstable [2]. Reliable monitoring of the deformations of existing and planned engineering structures on the Oder islands in Szczecin justified the planned and implementation of an appropriate control and measurement system (Table 1). This system was successfully implemented in 3D deformation studies relating to several critical engineering structures and geodynamic testing grounds [3–5].

Table 1. Characteristic of a control and measurement system for 1D space testing

	Segment I	Segment II	Segment III
Measuring method Measuring instrument	Precision levelling	Total station Precision levelling	Exstensometr, Feelergate, Dilatometer
Frequency of Observation	1–2 years	3 months	1–30 days or permanently
Accuracy of displacement determination	±(0.5) mm	±(0.5–2) mm	±(0.01–0.1) mm

The first step of this task was to locate stable reference points (benchmarks removed outside the islands on geologically stable sands) in the field in a 1D space as the first segment of the system (Figure 1). The analysis of the first (measurements of the difference in height between the benchmarks performed with a precision levelling nivelator with an accuracy of 1 mm/km) and second class (measurements of the difference in height between the benchmarks performed with a precision levelling nivelator with an accuracy of 2 mm/km) levelling lines enabled the selection of one more reference points for the first segment of the control and measurement system. This allow observations of of measurement of surface displacements that are inferred as resulting from deformation of the organic deposits of the Szczecin surface area to be conducted in a 3D space [5], also using GNSS observations. This has been done based on the analysis of height changes of the benchmarks on one of the state lines of second class levelling, passing through the Międzyodrze area near the EcoGenerator (Figure 1). Height changes were measured between 1975 and 2000 year. The area of the EcoGenerator Waste Disposal Plant is part of the research area. For the specific location of the stable reference benchmarks (benchmarks 1 and 3) a detailed understanding of the geological structure [6] of the subsoil in the vicinity of these points was necessary. The results of the implementation of these works are presented in Section 4. An example of the second segment of the control and measurement system, concerns the monitoring of the deformation of the EcoGenerator structure. The works in this scope are in the initial phase. One of the reference points is Point 4 (Figures 1 and 2), which belongs to the second segment of this system. Points 4, 8, 14, 17′, 11′, 7′ (Figures 1 and 3) are Class 2 benchmarks (benchmarks, the deifference heights of which were measured with an accuracy of 2 mm/km), the observations of which are related to stable (benchmarks 1 and 3).

Regardless of the aforementioned control and measurement system, the vertical movements of land in the EcoGenerator area during its construction and initial operation (2014–2019) were investigated. The results of these studies with the use of InSAR satellite technology are presented in Section 4.2. The analysis of changes in the height of the first and second class benchmarks is innovative due to the reference of observations to benchmarks located in geologically stable regions of the city. Innovation consists in the integration of various observation techniques into one control and measurement system and the selection of techniques and system segments depends on the geological structure of the subsoil of a given region.

2. Characteristics of the Geological Structure of the Szczecin and the Engineering Structure

The location of Szczecin and its surroundings, set against the background of the main structural units of Poland is described in [7]. The geological structure of Szczecin [8] and its cross-section is shown in Figures 1 and 3. The formations of the campan (the upper chalk) lie at the bottom of the lowering stretching south of the city of Szczecin. They are formed in the form of carbonate rocks (limestone, rocks with chalk) and carbonate and silty rocks (marl, chalk) [6]. Within the Szczecin Basin the thickness of these sediments reaches 400 m. Salt movements occurring in deeper Permian and Triassic formations (clays, siltstones, limestone) resulted in the formation of numerous fragments cut by faults within them. In the area of Szczecin's anticline, a part of the mastrycht sediment cover (the upper chalk) was torn off and an "erosion windows" of the campan were created. This separation was not only due to erosive reasons. It was also caused by lifting movements in the regions of salt structures [6]. Within the Cenozoic, older Palaeogene formations - oligocene and younger neogen-myocene and younger forms-pleistocene and holocene - can be separated (Figures 1 and 3). The oligocene formations are septic clay-dusty, weakly calcified clays with gypsum crystals, clay, sandy silt, silt and glauconite sands (Figure 3) [8]. The thickness of these formations ranges from 12 m in the central area of the city centre of Szczecin, to several dozen metres within the Międzyodrze islands. It has been identified by numerous boreholes [8]. The neogene (pleistocene) formations are clay (the northern Poland glaciation). The neogene (holocene) formations are sands and clays in the downtown area of Szczecin and organic soils (peat, mud, gyttjas) Figures 1–3. The characteristic feature of organic soils is their low shear strength and high compressibility [8]. This is caused by the presence of organic substances and the colloidal liquid phase in their composition. The thickness of the whole organic series around Oder River reaches a maximum of 13 m [8]. The change in the nature of the buildings (lack of proper soil compaction) within the city over the last hundred years has increased the load on the organic land, which has led to its compaction [9]. The Międzyodrze area is a narrow strip of the Oder valley adjacent to the Oder riverbed (Figure 1).

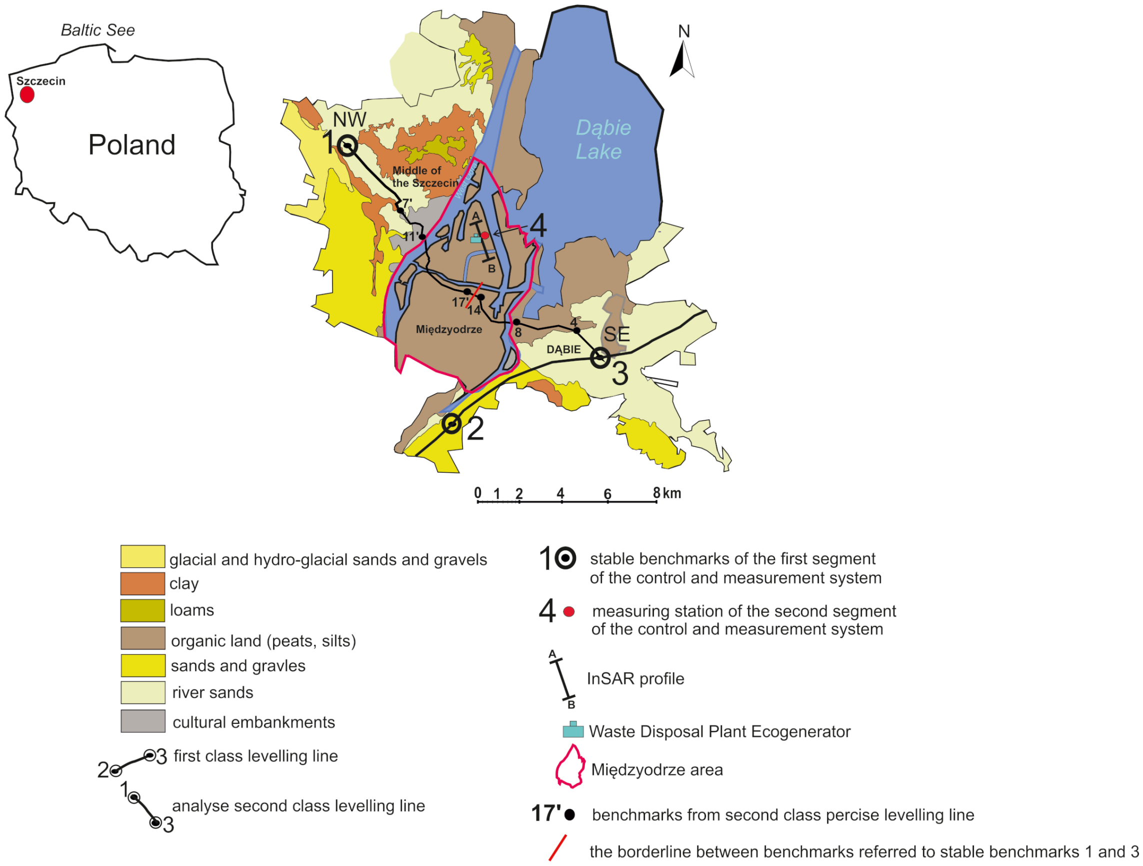

Figure 1. Geological map of the Szczecin area with certain benchmarks between stable points.

The thickness of organic land in this zone reaches 18 m. These sediments are under load of uncontrolled embankments up to 11.4 m thick [8]. The embankment is formed of sands containing silt and humus, together with fragments of bricks, rubble, wood and shells. The bedding sands are of a medium thickness; these are the holocene sands, originating from the river. Locally, organic soils vary in type and thickness.

The organic land in the area of the Międzyodrze River consists of 8.8 m of peat. In the rest area, the thickness is 2 m, is 7 m thick [8]. Figure 1 shows the course of the second-class precision levelling sequence with stable points 1 and 3 of the first segment of the control and measurement system. The InSAR cross-section (A-B), marked in Figure 1 is located approximately 3 km to the Northeast of the analysed Class 2 sequence.

The substrate of the Waste Treatment Plant EcoGenerator (Figure 2) is formed by organic soils (peat, gyttjas, mud) and sands. Their thickness varies from 4 m to 9 m [10]. These soils are covered with a layer of uncontrolled embankments with a thickness of up to 8 m [10].

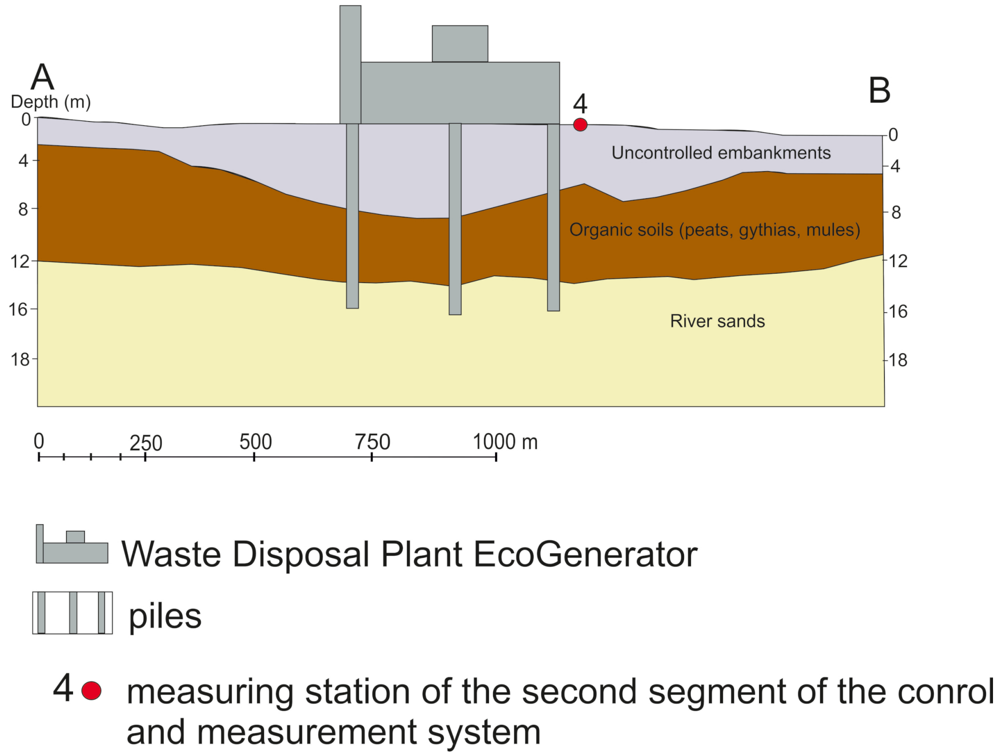

Figure 2. Geological structure of the Waste Disposal Plant EcoGenerator site show across A-B profile.

Layer of uncontrolled embankments was fertilized before the construction of the facility began in order to induce the settlement of organic soil [10]. The EcoGenerator facility was set on fire (Figure 2).

3. Methods

When organizing the first segment of the control and measurement system, the analysis of the speed of changes in the height of the benchmarks on the second class (measurements of the difference in height between the benchmarks performed with a precision levelling nivelator with an accuracy of 2 mm/km). Two stable benchmarks, 1 and 3 were located on it. The result of these works is presented in Section 4.1. The analysis of the 1-line class (measurements of the difference in height between the benchmarks performed with a precision levelling nivelator with an accuracy of 1 mm/km) was carried out in a similar way, which enabled Benchmark no. 2 (Figure 1) to be located. This third geologically stable point in the area of Szczecin will also form the basis for the studies of organic deposits surface deformation and engineering structures in 3D space using GNSS [4]. The next stage of the planned works will be an appropriate implementation of the second segment of the control and measurement system (with Point 4) to observe the deformation of the EcoGenerator structure with the use of precision levelling and total station. The organization of the third segment of the control and measurement system, with reference to Point 4, will consist of the installation of instruments for the relative monitoring of the structure's deformation, using instruments such as a feelergate, an inclinometer and an extensometr.

Precision levelling shows the vertical changes in the terrain surface from 1975–2000 to the second class between benchmarks considered stable. This sequence does not pass through the EcoGenerator plant area. The InSAR studies, on the other hand, are of a surface character limited to the Międzyodrze islands. They were conducted in the years 2014–2019. At this stage of the research implementation, the first segment of the control and measurement system was organized. The results of these works are presented in Section 4.1. InSAR analysis is only used for very broad identification of the moving area. During this research work, Satellite Radar Interferometry (InSAR) [11,12] was used to determine the vertical changes of the rock mass surface in the Międzyodrze area with particular emphasis on the area around the EcoGenerator. These studies were carried out during the period 2014–2019 and related to the preparation of the site for the construction of this structure and the beginning of its exploitation. During the preparation of the investment, the area underwent significant changes, relating to the consolidation of the surface layer of the rock mass through the fertilization of the embankment land on unstable organic deposits (peat, gyttjas, mud). The effects of this method are presented in Section 4.2. This enabled changes in the organic deposits surface to be recorded across a wide range of terrain [13].

The analysis of the organic deposits surface deformation in the area of the city of Szczecin was based on radar data from Sentinel 1A and 1B satellites (Path 73). In the calculations, a total of 129 images were used, covering the period from 15.11.2014 to 28.07.2019. The calculations were based on the SBAS method, which repeatedly uses master images with a fixed base limit (both spatial and temporal base). This limited the impact of geometric decorrelation [11]. The SBAS method usually achieves the best results for areas with scattered reflective objects, (i.e., areas where there are no dominant reflective objects). This also applies to image sets; their spatial-temporal distribution of bases allows a graph to be created that links all images in a set. The results obtained using this method from the area of the EcoGenerator Waste Treatment Plant, are presented in Section 4.2.

4. Results

4.1. Analysis of Changes in the Height of the Benchmarks on the sEcond Class Levelling Line

An analysis of the heights of the benchmarks on the second class precision levelling line, measured in 1975 and 2000 in the area of Międzyodrze and the city was carried out.

A proprietary reference system was created to determine credible changes in the height of the benchmarks between the measuring periods. For this purpose, the differences in height between the neighbouring benchmarks measured across two measurement campaigns (1975 and 2000) on the first and second class levelling lines were used. The differences in the variance of three exceedances amongst the adjacent four benchmarks were analysed. Values which did not exceed the average error (RMSE) of these changes were regarded as stable. The location of particular reference benchmarks still met the condition of "stable" geology. Figures 1 and 4 show the locations of selected benchmarks set against the background of the geological structure.

The relevant average error (RMSE) and speed of changes in the height of the benchmarks were calculated based on certain formulae [14] as follows:

- RMSE average variation in excess,

$$m_{r,\triangle hi} = \pm m_{\triangle hi} \cdot \sqrt{2} \tag{1}$$

  where: $m_{\triangle hi}$—RMSE of the i-th overrun, $m_{r,\triangle hi}$—RMSE of the i-th difference in elevation,
- the speed at which the altitude changes,

$$V_{n,n+1} = \frac{\triangle H_{n,n+1}}{T_{n,n+1} - T_n} \tag{2}$$

  where: $V_{n,n+1}$ - speed of changes in altitude of benchmarks in the period between n and $n + 1$, $H_{n,n+1}$—the difference in height of benchmarks between epochs, T_n—year of the measurement epoch n, T_{n-1}—year of the measurement epoch $n + 1$,

- RMSE speed change in altitude,

$$m_{V_{n,n+1}} = \pm\sqrt{\frac{2 \cdot m_0^2 \cdot R_i}{(T_{n+1} - T_n)^2}} \quad (3)$$

where: m_0—RMSE nivelation over a distance of 1 km, $m_{V_{n,n+1}}$—RMSE speed change in altitude, R_i—distance of the *i-th* episode from the reference benchmark of a given line, T_n—year of the measurement epoch n, T_{n+1}—year of the measurement epoch $n + 1$.

Table 2 presents the changes in height of the benchmarks in the Międzyodrze area during the period 1975–2000. First of all, the differences in the height of the neighbouring benchmarks were calculated. Next, new heights were calculated in relation to the stable benchmarks. The values of the velocity of changes in the height of the benchmarks on the Oder Islands exceeded −0.11 mm/year. The regions of Szczecin City Centre and the Dabie district (Figures 1 and 3) were stable. Changes of most of the benchmark heights were at or near 0.0 mm.

Table 2. Vertical movements of the benchmarks on the second class line in the Międzyodrze area

Benchmarks	Distance from Fixed Benchmark R [km]	Height Changed 1975–2000 [mm]	Height Changed Speed 1975–2000 [mm/year]	RMSE of the Speed of Change of Altitude ± mV 1975–2000 [mm/year]	Area
1	**0.00**	**0.0**	**0.00**	**0.00**	DĄBIE
1	1.00	−0.2	0.00	0.03	
2	1.89	0.2	0.00	0.05	
3	2.54	1.02	0.05	0.07	
4	3.11	17.09	**0.72**	0.08	
5	3.51	0.2	0.00	0.10	
6	3.87	−0.2	0.00	0.10	
7	4.41	0.0	0.00	0.10	
8	4.54	0.0	0.00	0.10	
9	6.55	−3.9	−0.16	0.12	MIEDZYODRZE
10	7.81	−4.0	−**0.16**	0.14	
11	8.41	−4.1	−**0.16**	0.14	
12	9.03	−4.1	−**0.16**	0.15	
13	10.41	−4.3	−**0.17**	0.16	
14	11.51	−63.1	−**2.52**	0.19	
17′	8.02	−2.8	−0.11	0.16	
16′	6.97	−2.8	−0.11	0.13	
15′	6.50	−2.9	−0.12	0.12	
14′	5.74	−3.0	−0.12	0.12	
13′	5.54	−3.1	−**0.12**	0.11	
12′	5.35	−3.1	−**0.12**	0.11	
11′	4.97	0.0	0.00	0.10	MIDDLE OF THE SZCZECIN
10′	4.77	0.0	0.00	0.10	
9′	4.75	−0.5	−0.02	0.10	
8′	4.63	0.1	0.00	0.10	
7′	3.52	−13.0	−**0.52**	0.09	
6′	3.07	0.5	0.02	0.08	
5′	2.84	0.5	0.02	0.08	
4′	2.21	0.3	0.01	0.06	
3′	1.77	0.0	0.00	0.06	
2′	1.24	0.0	0.00	0.04	
1′	0.38	0.0	0.00	0.03	
3	**0.00**	**0.0**	**0.00**	**0.00**	

The area of the Międzyodrze islands is threatened by deformations of engineering structures, which are caused by the settlement of organic land. Eight benchmarks in the area of the islands exceeded the RSME speed of altitude changes. These speeds reached values of between −0.12 mm/year and −0.17 mm/year. A single benchmark (14) showed a significant value (−2.52 mm/year) of height change rates. This was the result of an increased land load in the area of the expanded port quay. The remaining height change velocities of the benchmarks were within the limits of the RSME error.

In the area of Szczecin City Centre (Figure 3), the speed of the height change of one point (7′) reached −0.52 mm/year. This was probably the result of the settlement of the building, in the foundation of which the benchmark was settling.

In the Dabie district, near the lake of the same name, one benchmark (4) showed upward movements of +0.72 mm/year during the period 1975–2000. This was an effect of the rise in height of the water table in Dabie Lake.

The values of the speed of changes in the height of the benchmarks in the Międzyodrze area were higher by comparison with the rest of the city. This underlines the unstable geological structure of the area.

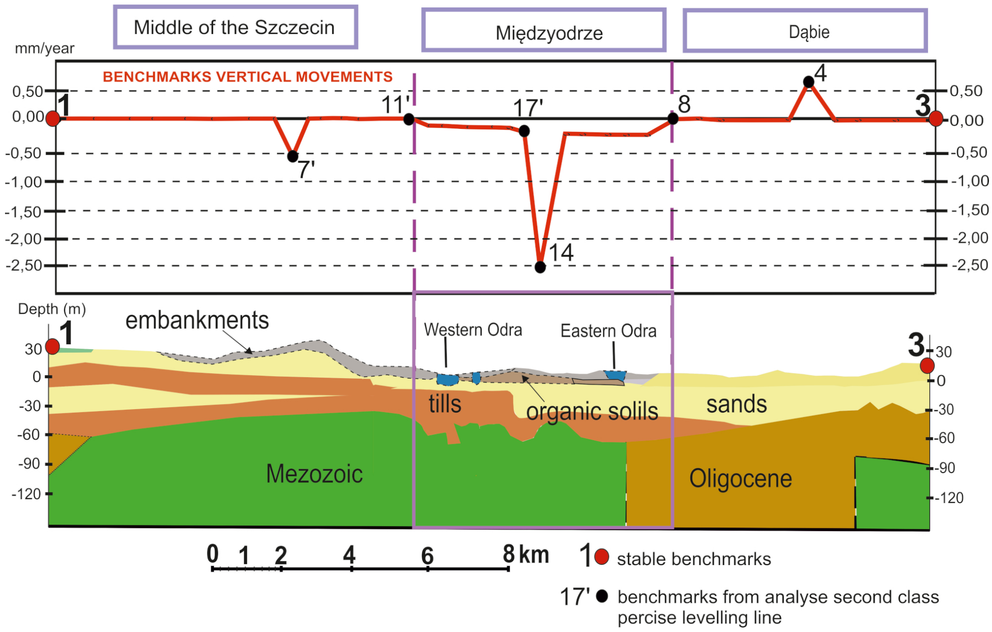

Figure 3. Geological cross sections with vertical movements of benchmarks between stable points.

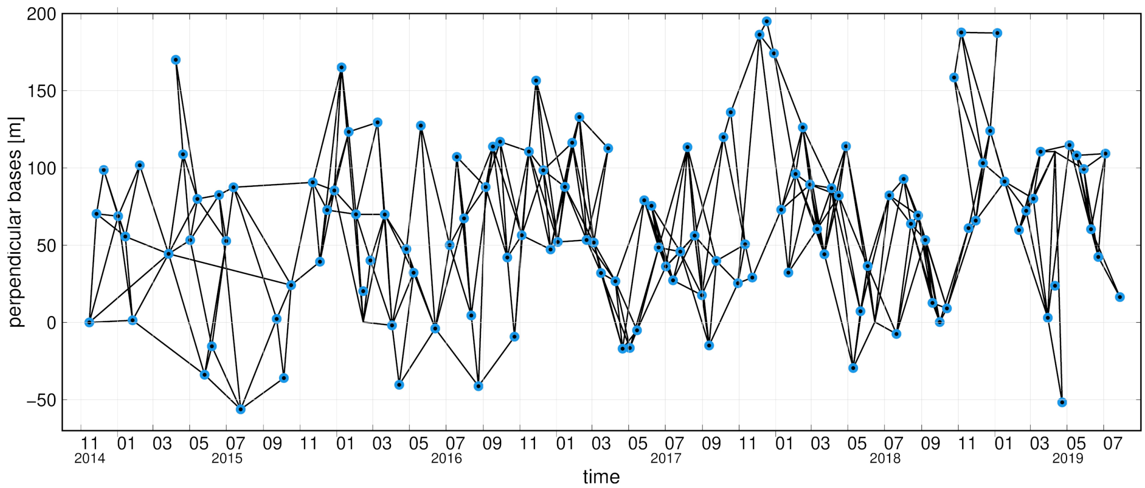

Figure 4. Baseline plot for used SAR datasets from track 73.

4.2. Analysis of Changes in Displacement Values Obtained Using InSAR

Displacements were determined for 129 equal 12-day intervals. The geological structure of the area around the EcoGenerator is shown in Figure 2. Pairs of images were determined at the pre-processing stage, from which a total of 324 interferograms were calculated. The calculations were based on GMTSAR software [15]. The development of the waveform phase was carried out using Snaphu software [16]. Shuttle Radar Topography Mission (SRTM) version 1 data were used to correct the wavelength phase relative to the ground surface [17]. At the pre-processing stage, the enhanced spectral diversity (ESD) algorithm was used. Basic information concerning the data set for the analysed path (73) are presented in Table 3.

Table 3. Summary of basic information on the data radar used.

Item	Attribute
satellite	Sentinel 1A/1B
path number	73
sensor mode	IW 1
incidence angle	33.54°
analysis time	from 15.11.2014 to 28.07.2019
amount of data SAR	129
perpendicular baselines	50 [m]
time baselines	40 [days]
total number of interferograms	329

The application of the Small Baseline Subset Method [18] shows anthropogenic values of vertical displacements of the rock mass surface within the inter-odder islands to a greater extent (Figure 1). These values in the EcoGenerator area, during the years 2014–2019, shown using this technique, reached −483 mm (Figures 5 and 6).

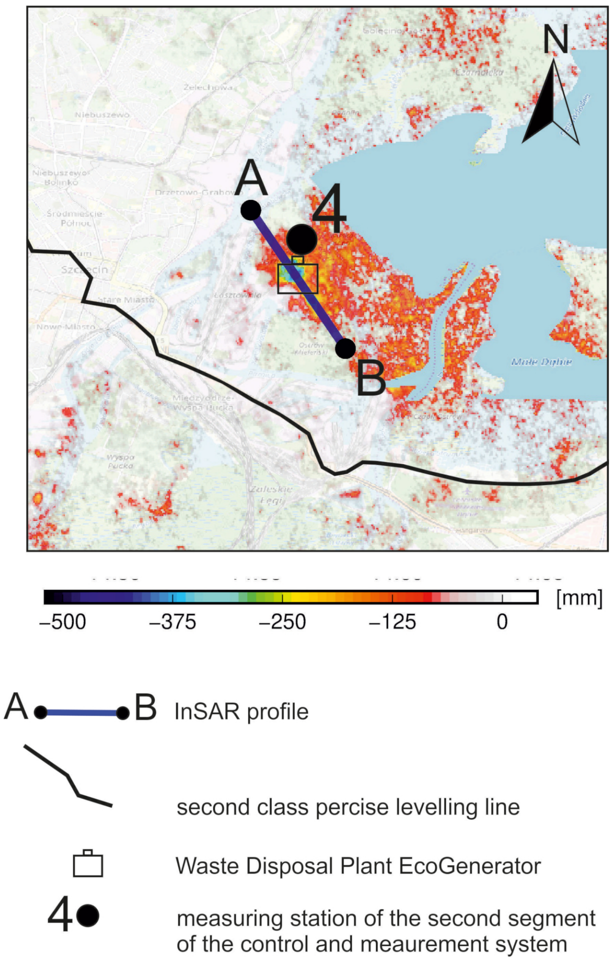

Figure 5. Values of changes in the height of the rock mass surface in the EcoGenerator area.

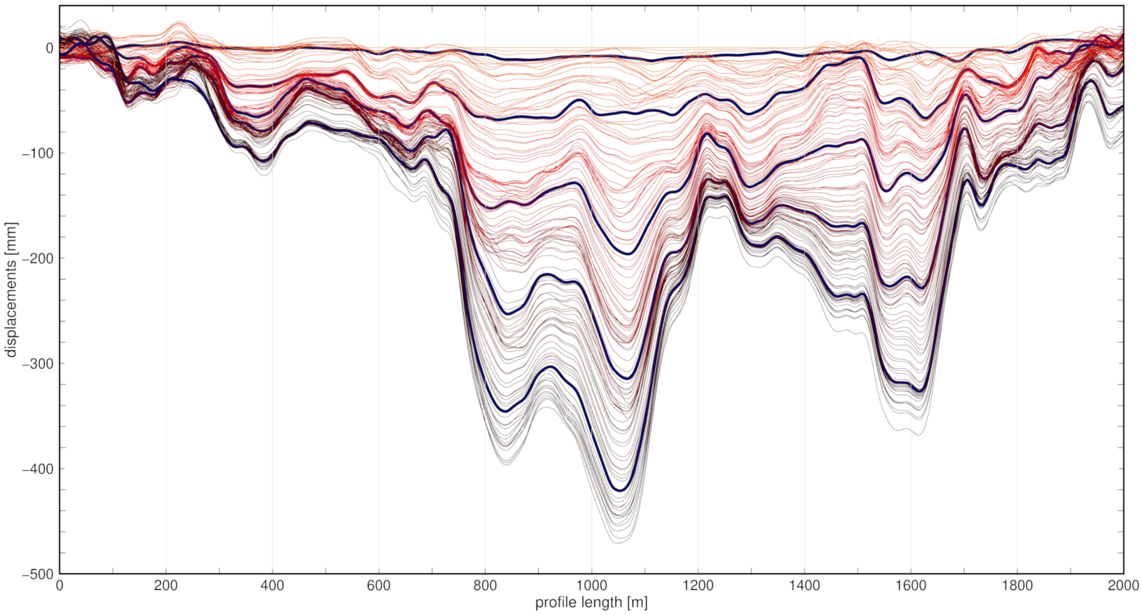

Figure 6. Vertical displacement values obtained using the InSAR Small Baseline Subset Method.

Vertical movements reaching −483 mm during the period 2014–2019 may indicate the loading of the native substratum of the plant with a layer of embankments before the beginning of construction and at the beginning of its operation (Figure 2).

5. Discussion

A geodetic control and measurement system was implemented to monitor deformations of the organic deposits surface and engineering structures in 1D space on the Międzyodrze islands in Szczecin. If necessary, it can be extended to 3D deformation measurements. The condition for this task is a minimum of the third reference point (2) in the first segment of the system, which was located on the first class levelling line. Substantive and economic reasons justify the introduction of GNSS satellite technology (instead of precision levelling) for periodical observations of reference points located several kilometres away. This solution has been successfully proven in similar studies on several engineering structures and geodynamic training grounds [3,5]. In connection with the modernization of Wrocław city's altimetric warp [4], the lack of stability of deep-sea benchmarks in the city area was also demonstrated.

It is still necessary to pay attention to the reliability of the deformation measurement results of engineering structures. Deformations are a phenomenon occurring in space and time. The most important factor of space is the reference system, and time is the moment when measurements begin. The most frequent causes of known, tragic catastrophes relating to the failure of critical structures (dams, viaducts, landslides, etc.) are the improper organization of the deformation measurements of these structures. In such conditions, it is not possible to register a reliable beginning of dangerous changes in the composition of a structure. As a rule, reference points are located at a short distance from the object, in the same geological structure. On the other hand, deformation tests on the intact surface of the organic deposits are usually delayed until after the construction of the structure instead of being carried out before the commencement of the earthworks on the intact surface of the rock mass. As a consequence, the specialist interpretation of the results of such measurements of the structure's deformation refers to the effects of the deformation, not the cause-effects.

An organized control and measurement system on the Międzyodrze islands in Szczecin to register the deformation of the EcoGenerator structure, protects the space factor (reference system) of this and new planned structures. Unfortunately (not due to the fault of the authors of the article) commencement of the deformation study of the existing building has been delayed. It is hoped that the investors in buildings planned for Międzyodrze will take this time factor into account, when designing a reliable monitoring system of the deformation of these structures. It should be noted that the studies on changes in the surface of the organic deposits, using the InSAR method presented in this paper, despite their commencement before the construction of the EcoGenerator, do not meet the substantive requirements.

6. Conclusions

The implemented method of surveying the deformation of the organic deposits surface and engineering structures in the area of Międzyodrze in Szczecin is a "tool" aimed at providing reliable results with regard to their safety. The flat terrain of the Oder islands justified the creation of a three-segment control and measurement system to monitor deformations in 1D space. It is based on the first segment forming a stable reference system. To locate at least two benchmarks (1, 3) of this system, the archival results of measurements of basic levelling lines recorded between 1975 and 2000 were used. The appropriate procedure to compare changes in the height of the benchmarks and stable geological substratum, provided the basis to choose the location of these points (Figure 1). This stage of work has been completed.

The second segment of this system is in the initial phase of its implementation. The pilot engineering structure for testing vertical deformations is the EcoGenerator (Figure 2). A point (4) was located in the vicinity of the structure on unstable geological substratum. The current height of the point will be related to the first segment benchmarks. Periodic measurements of the benchmarks installed in the foundations of the EcoGenerator, are planned. The area of the EcoGenerator Waste Disposal Plant is part of the research area.

The third segment of the control and measurement system will be based on observations of relative displacements of the structure on expansion joints, fractures, etc., using devices such as an extensometer, a fracture meter and a dilatometer.

Vertical surface changes in the EcoGenerator's surroundings, determined by the InSAR method and reaching values of over 45 cm, confirm the complex problem of instability on the Międzyodrze islands. InSAR analysis is only used for very broad identification of the moving area. A comparison of these with the results of the analysis of changes in the height of the benchmarks, is not justified in terms of merit. This is due to the fact that a loose layer of fertilized soil is present in order to stiffen the organic geological structure.

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References

1. Kozińska, B. (Ed.) *Spatial Development of Szczecin from the Beginning of the 19th Century to the Second World War*; Association of Art historians. Szczecin Branch; National Museum in Szczecin: Szczecin, Poland, 2002. (In Polish)
2. Krygowski, B. About the relationship between the sculpture of today's surface and the structure of the ground in Szczecin Pomerania. *Sci. Notebooks Adam Mickiewicz Univ. Poznań* **1959**, *2*, 69–86. (In Polish)
3. Caconń, S. The measurements and monitoring systems with GPS-the basis for reliable data on deformation of an engineering object. In Proceedings of the XXI International Congress FIG, Commission 6, Brighton, UK, 19–25 July 1998; pp. 530–540.
4. Cacoń, S.; Bosy, J.B.K. The GPS levelling network in the conurbation of Wrocław. *Artif. Satell.* **1999**, *2*, 163–170.

5. Cacoń, S.; Kontny, B.; Bosy, J. 3 D monitoring of the selected active tectonic structures in Poland, Italy and Greece. *Acta Geodyn. Geomater.* **2007**, *4*, 7–17.
6. Dobracki, R. *Explanations to the Detailed Geological Map of Poland in the Scale 1:50,000, Sheet Szczecin (228)*; Technical Report; Geological Surveyes: Warszawa, Poland, 1982. (In Polish)
7. Żelaźniewicz, A.; Paweł, A.; Buła, Z.; Karnkowski, P.; Konon, A.; Andrzej, Ś.; Żaba, J.; Żytko, K. *Tectonic Subdivision of Poland*; Tectonic Regionalisation of Poland, Committee of Geological Sciences PAN: Wrocław, Poland, 2011; pp. 8–14. (In Polish)
8. Piotrowski, A.; Rielsko-Rybak, J.; Sydor, P. "Szczecin on stilts" - geological and engineering conditions of the foundation of the city and port in the Oder Valley. In Proceedings of the LXXX Scientific Congress of the Polish Geological Society, Szczecin, Poland, 11–14 August 2010. (In Polish)
9. Tarnawski, M. *Geological-Engineering Studies of Weak-Bearing Soils in the Lower Oder Valley; Guide LV of the PTG Congress 16–18 August, 1983 Szczecin*; Geological Surveyes: Warszawa, Poland, 1983; pp. 178–180. (In Polish)
10. Wolak, B. *Engineering-Geological Documentation of the Subsoil for the Disposal Plant EcoGenerator*; Geotechnical Consulting Office: Szczecin, Poland, 2015. (In Polish)
11. Milczarek, W. Application of a small baseline subset time series method with atmospheric correction in monitoring results of mining activity on ground surface and in detecting induced seismic events. *Remote Sens.* **2019**, *11*, 1008. [CrossRef]
12. Rucker, M.L.; Panda, B.B.; Meyers, R.A.; Lommler, J.C. Using InSAR to detect subsidence at brine wells, sinkhole sites, and mines. *Carbonates Evaporites* **2013**, *28*, 141–147. [CrossRef]
13. Ratkajec, M.; Kapovic, Z.; Mastelic-Ivic, S. Combination of GPS and Precise Levelling in Measurements of Vertical Bridge Deformations. *Acta Geod. Geophys. Hung.* **2000**, *35*, 219–226. [CrossRef]
14. Wyrzykowski, T. *Precision Levelling*, 2nd ed.; Polish Cartographic Publishing Enterprise: Warszawa-Wrocław, Poland, 1993. (In Polish)
15. Sandwell, D.; Mellors, R.; Tong, X.; Wei, M.; Wessel, P. Open radar interferometry software for mapping surface Deformation. *Eos Trans. Am. Geophys. Union* **2011**, *92*, 234. [CrossRef]
16. Chen, C.W.; Zebker, H.A. Network approaches to two-dimensional phase unwrapping: Intractability and two new algorithms. *J. Opt. Soc. Am. A* **2000**, *17*, 401–414. [CrossRef] [PubMed]
17. Farr, T.; Rosen, P.A.; Caro, E.; Crippen, R.; Duren, R.; Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; et al. The shuttle radar topography mission. *Rev. Geophys.* **2007**, *45*, 1–33. [CrossRef]
18. Berardino, P.; Fornaro, G.; Lanari, R.; Sansosti, E. A new algorithm for surface deformation monitoring based on small baseline differential {SAR} interferograms. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 2375–2383. [CrossRef]