Research Article

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Multi-temporal survey of diaphragm wall with terrestrial laser scanning method

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Abstract: The development of measurement technologies allows for acquiring various data. The Terrestrial Laser Scanning (TLS) technology is frequently combined with classic geodetic measurements – tacheometry or levelling. This article presents a process of the diaphragm wall monitoring during excavation supported with a top-down method. The construction technology applied required proper planning and performance of measurements in difficult construction site conditions in the city centre. TLS allowed for limiting works at daytime and performing monitoring during the night break in works at the construction site as well as limiting the impact of the subsoil process vibrations on the values of displacements and deformations determined. The authors present a comparison of the results of displacement and deformation measurements with a terrestrial laser scanning and tacheometric measurement method. The possibilities of using the data acquired, among others, for the indication of filtration areas, spatial surface deformation analyses and assessment of the wall execution compliance with the design are presented. The analyses carried out show that the TLS may be used in the investment process from the very beginning, being a component of the Building Information Modelling (BIM).

Keywords: engineering geodesy, monitoring, terrestrial laser scanning, building information modelling, investment process

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1 Introduction

In the era of constant development of cities and a growing demand for service facilities such as office buildings and shopping centres and the related limitations in the location of hundreds of parking spaces, new investment projects, usually with a few-storey underground parts, are realized in the city centres with dense housing and infrastructure. Such facilities exert an impact on neighbouring developments under construction as well as those already in existence [1]. Simultaneously, development of municipal infrastructure involves the construction of tunnels and underground stations with the use of various technologies and demolition of old buildings. In an urban environment, impacts of various new investment projects may overlap. The disaster of Europlex in Warsaw in 1998 [2] or problems related to the impact of Line II of Warsaw Metro in the area of Świętokrzyska and Centrum Nauki Kopernik (Powiśle) stations [3] may serve as examples of how serious the effects of the impact of executed projects in urban areas may be.

A deep excavation, in accordance with currently applicable standards, is an excavation with vertical, cased walls, with the depth of not less than 3 m. A term used more frequently (though having a broader meaning) is a deep-seated construction facility. The term denotes a deep excavation with the casing of sunk walls as defined by Eurocode 7 [4].

The impact of deep foundations on the surrounding environment may be divided into two groups:

1. physical (resulting from the centre mechanics and the process of its unloading and loading), hereinafter referred to as natural,
2. process (resulting from the conditions of the project, related to the adopted solutions and care of execution).

1.1 Monitoring the walls of the excavations

Displacements measured are the effect of the aforementioned impacts. Vertical displacements appear to be caused rather by natural impacts, whereas horizontal displacements result mainly from process impacts [5].

Natural impacts are the result of the changes in the stress level in the subsoil during the execution of both the excavation and the facility itself, resulting successively from: unloading the subsoil while executing the excavation, secondary load and extra load.

The scope and volume of process impact depend on the impact of the adopted solutions on the changes in the ground base stress level. These include, above all: the kind and the method of the casing execution, changes in the stress level while trenching the gap in which diaphragm walls will be executed, dynamic loads during the wall execution, the kind of support or anchoring of the casing (initial prestressing or strutting), the method and time of excavation trenching, the impact of the excavation drainage (the method of lowering the groundwater table), subsoil strengthening under neighbouring facilities and human factor [6]).

The impact of deep foundations on the environment is complex and each investment requires a separate analysis. The greatest impact on the volume of displacements is exerted by the kind and the condition of the soil (the parameter defining stiffness thereof) in which the excavation is executed, the depth of the excavation as well as the quality, carefulness and pace of works execution. Duration of works execution is a very important aspect, as an interruption in the works execution always causes an increase in the value of displacements in the area of the excavation, in comparison with the execution in accordance with the schedule.

The execution of a deep-seated facility may be carried out when the excavation is protected with use of one of the most frequently used vertical soil support solutions:

1. cantilevered or anchored Berlin type pit lining,
2. Larssen sheet piling,
3. cantilevered, anchored or strutted sheet piling,
4. floor or top-down method (see Figure 1).

Each of the aforementioned excavation wall protection methods limits the possibilities of performing control measurements in a different way. Cantilevered or anchored walls require formwork at successive storeys and this formwork often covers the monitored wall. At the stage of execution of the structure at the foundation slab, walls are quickly built-in. A temporary possibility of the observation of the entire uncovered wall prior to its building-in is a definite advantage from the point of view of geodetic monitoring.

Monitoring of the construction behaviour during the construction of the underground part should include performing geodetic control measurements at specific stages of construction works. Control measurements should be performed after the completion of successive stages of the excavation trenching and other works such as excavation drainage or construction of extra protection measures (cantilevers, struts, anchors). The scope of measurement works carried out should be determined individually for each facility depending on the possible hazards. In the case of diaphragm walls, most often monitored points include points located at the wall cap and in the underground part, control points at selected vertical structure profiles (at least one profile in the middle of each straight section of the wall and in locations indicated by the designer).

The periodical nature of measurements allows for the consideration of the time factor and changes in load levels while elaborating the results and performing analyses of the structure element displacement and deformation.

Monitoring the walls of excavation supported with the top-down methods (see Figure 1) is particularly difficult due to the necessity of performing separate measurements at successive storeys and a limited observation horizon for benchmarks located out of the construction works' impact zone.

Different kinds of measurements are used to monitor deep excavation walls, namely geodetic and geotechnical ones. Both absolute and relative measurements are carried out. The former refers to the system located out of the range of the construction impact. The latter depicts the behaviour of the walls in relation to one another and to other foundation elements. Modern techniques of imagery such as laser scanning technology are more frequently employed these days.

1.2 Laser scanning technology

Laser scanning technology can be distinguished into two categories: Terrestrial Laser Scanning (TLS) and Airbone Laser Scanning (ALS). The appropriate technique is chosen, depending on the type of report and research; however, each can be used in surface research, landslide research and engineering object measurements. Due to the different nature of data in TLS and ALS, this article concentrates on using data from TLS. TLS is used in many fields, including engineering surveying [7] and recent developments show its suitability to control deep excavation supports [8].

The past decade has been clearly dominated by the TLS technology, both in scientific terms (a large number

Figure 1: Excavation supported with a top-down method (photograph by Janina Zaczek-Peplinska).

of publications on TLS coming out in the period) and commercial use of laser scanner and the technology itself. Despite a relatively low precision of determination of the location of a single point, laser scanning has a great advantage – it enables registration of the condition of the entire scanned facility. Over a short period of time, it is possible to obtain quasi-continuous, fully metrical, spatial representation of the surface of the measured facility in the form of a point cloud [9]. Having analysed the data recorded in several periods, it is possible to analyse the deformations of entire surfaces as well as deformations of structural elements, referring to the changes in the whole object globally, not locally as with methods based on the determination of a single point displacement (geodetic methods of angular–linear measurements). This aspect poses a great advantage over conventional, classic measurement methods such as tacheometry [10]. Having a point model characterized by quasi-continuity at one's disposal, one may carry out a number of geometric analyses in post-processing as well as obtain information for further, detailed analytical considerations [7]. The fact that the aforementioned analyses may be carried out in any place of the scanned/measured facility, and not – as in the case of classic methods – only in locations for which the measurements were performed, constitutes an unquestionable advantage.

In the publication [11], the author points out the fact that TLS may replace traditional measurement methods e.g. the ones that require the application of distance measurements. The technology enables gathering digital data in the form of point clouds which may be used to create 3D models of facilities. Moreover, it allows for gathering data with a high precision, which translates into the possibility of recovering all structural elements.

As regards the subject matter of the article, it should be noticed that comparing the point clouds registered at various stages of the excavation execution allows for the performance of multi-temporal analyses and deflection of diaphragm wall deformations occurring over time.

In addition, based on the so-called fourth coordinate intensity (I) (intensity of a laser beam reflected from the measured surface) registered while scanning, spectral analyses of humidity of the measured wall surfaces as well as differentiation of materials used and the assessment of treatment and contamination of concrete surfaces after uncovering successive parts of the diaphragm wall while trenching the excavation are possible.

The fact that the measurements may be performed at night, not colliding with construction works, constitutes an additional advantage of the measurements performed with the TLS technique.

1.3 Integrated project execution process – Building Information Modelling (BIM)

Data acquired in the performed control survey during the construction may affect the time frame of realization of the investment, if they are used to systematically support the Integrated Project Execution Process. Thus, BIM providing the grounds for the Integrated Project Execution Process is gaining great popularity [12].

The American National BIM Standard describes BIM as "common resources of knowledge and information on the facility, constituting solid grounds for a decision during its life cycle, thus from the earliest stages of designing and construction to demolition" [13]. The implementation of the system of this kind is aimed at, among others, streamlining the investment process by means of a better correlation of works executed by representatives of various trades. Currently, during the execution of a facility contractors usually use a two-dimensional drawing made in CAD software in an electronic or hardcopy version. It should be emphasized that in accordance with legal regulations applicable in Poland, hardcopy versions of designs, bearing relevant stamps, are the binding documents. Such a work model, though tested for years, does not allow for full use of the capacity of current designing technologies, execution and control of the facility.

In the publication [12], the author describes the multi-dimensional nature of BIM. Successively, these may be the dimensions defined as follows:

1. linear, two-dimensional design most frequently used in a construction site,
2. 3D – three-dimensional spatial model,
3. 4D – three-dimensional model related to the schedule (facility execution timeline),
4. 5D contains all the aforementioned dimensions supplemented with a cost estimate i.e. the financial aspect.

In addition, [14] distinguishes two more BIM dimensions, namely:

1. 6D – the model in compliance with BIM, containing extra data, which allows for carrying out an analysis and optimization of the facility structure with respect to the fulfilment of sustainable construction postulates, at the stage of the design,
2. 7D – describes data supporting the management of the operation and maintenance of the completed facility, prepared in such a way that they can be implemented into the systems supporting facility management with ease.

As of today, the 2D model, dividing the construction into theme layers, is used in most construction sites in Poland.

Data obtained from laser scanning may be used at various stages of project execution, and within the operation period. In the publication [15], the author mentions the following applications of this technology in engineering and management: rapid urban-scale mapping/modelling, infrastructure asset management, construction site monitoring, structural analysis and inspection.

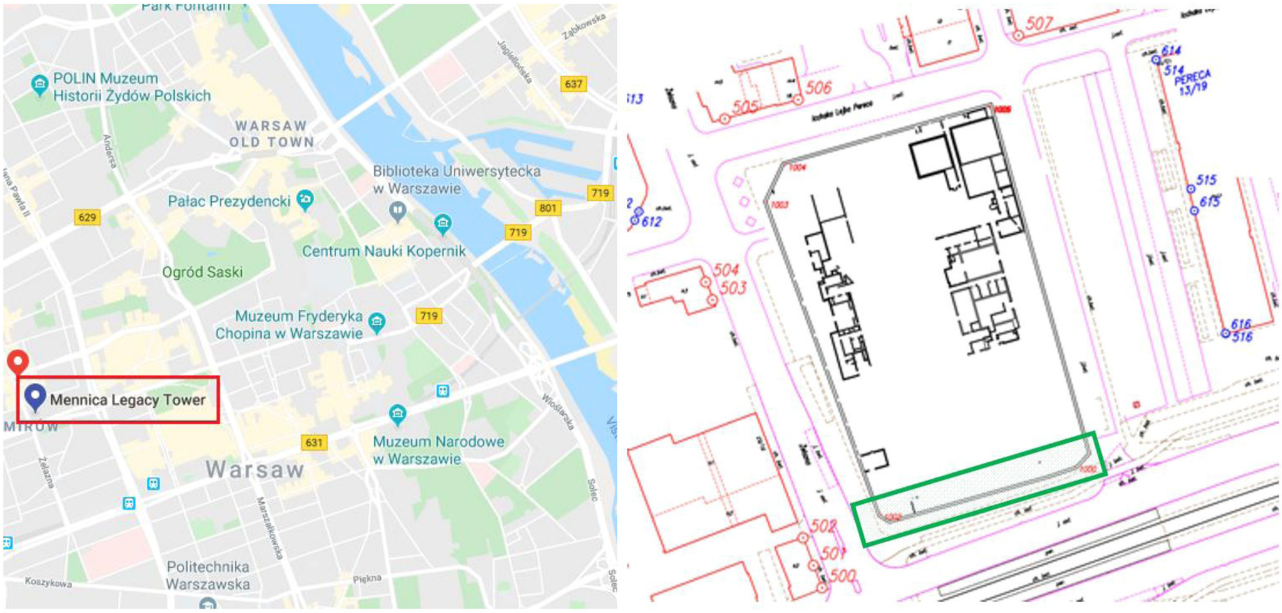
The authors of the article consider the possibility of supplementing the BIM system with data from the project monitoring as well as the analyses and inspection of the condition thereof. The data obtained with a TLS could constitute another aspect of BIM or supplement the 5D level.

The effective use of the BIM systems requires constant verification of the compliance of the design with the current status of its execution so as to implement adjustments having an impact on successive stages of works on an ongoing basis. Works may be performed manually, but TLS, which allows for surveying vast areas in detail over a very short period of time, serves the purpose well. Obviously, any changes, delays or errors have an impact on costs, thus the proposal of joining the financial aspect with the aspect of verification of the building permits design execution.

2 Study area and TLS data acquisition

The article describes the stages of a geodetic survey of the southern diaphragm wall of the excavation executed in the Mennica Legacy Tower building complex in the city centre of Warsaw (the investor: Golub GetHouse and Mennica Polska S.A.). The construction of the complex consisting of a 140 m tower (34 above-ground storeys, 4 underground storeys) and a neighbouring building with the height of 36 m (11 above-ground storeys, 4 underground storeys) was commenced in the fourth quarter of 2016 and it lasted till the end of September 2019 [16]. Figure 2 presents the location of the Mennica Legacy Tower facility, where the southern part of the wall, marked with a green frame, was surveyed with the TLS technology.

The survey of the southern part of the diaphragm wall was carried out with the use of two measurement



(a) (b)

Figure 2: (a) The location of the Mennica Legacy Tower. (b) Excavation with the diaphragm wall outline (black) and benchmarks along with their numbering (red ones are bifunctional *XY* and H benchmarks and blue ones have only *XY* coordinates), the southern part of the wall, surveyed with the TLS technology is marked with a green frame (Source: Google Maps, Warbud S.A.).

techniques – classic tacheometric measurements and TLS. For this purpose, a robotized tacheometer Leica TCRP 1201+ characterized by the direction measurement precision of 1″ and distance measurement precision of 1 mm + 1.5 ppm (reflective target) and 2 mm + 2 ppm for reflectorless distance was used for diagonal measurements. Laser scanning was performed with the Z+F Imager 5006h phase scanner emitting a laser light bundle with the length of 780 nm and allowing for obtaining point clouds with the speed of ca. 1 million points per second, at a distance of up to 79 m from the scanner. All measurements in both cycles were carried out with identical scanner settings i.e. “super high” scanning resolution and “high quality”. The average time of performance of a full scan at one station amounted to 13 min and 28 s.

Figure 3 presents the view of the diaphragm wall on the level –1 (–4.70 m). The photograph was taken during the first measurement cycle. A number of cantilevers limiting scanning scenes can be seen in the foreground. Due to the necessity of avoiding the wall coverage, nine scanner stations were located between cantilevers.

The first measurement cycle was made on 5 May 2017 at storey-1 of the complex (at that time in the northern part of the excavation, the trenching of storeys-2 and -3 was ongoing). Thirty measurement marks were arranged at the surveyed diaphragm wall and temporary poles. Tacheometric measurements were made from four tacheometer stations. The arrangement of the scanner and tacheometer observation stations is marked in Figure 4.

Figure 3: View of the diaphragm wall at level –1 (–4.70 m) (photograph by Janina Zaczek-Peplinska).

Two series of observations of the directions and distances to the measurement mark distributed were made from each tacheometer T1–T4 station, with reference to benchmarks located in buildings in the vicinity of the investment project (the red ones in Figure 2). Observations obtained in this way were subject to least

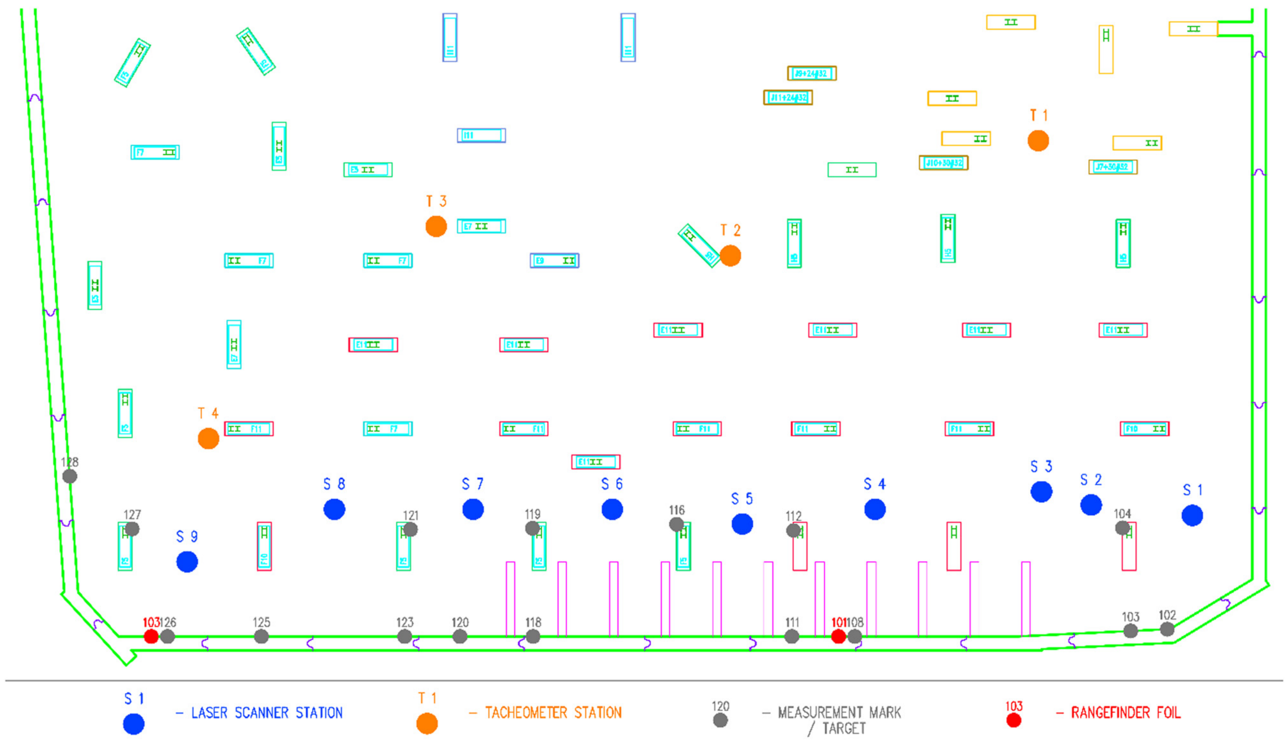


Figure 4: Draft of observation stations on a single underground storey: S1–S9 – laser scanner stations, T1–T4 – tacheometer stations, 102–128 (grey colour) measurement marks in the form of targets, 101 and 103 (red colour) control profiles – location of the reflective target.

squares adjustment, resulting in adjusted coordinates of the instrument and targets. Simultaneously – during the performance of classic measurements – the laser scanner registered point clouds successively from each station S1–S9. Point clouds were initially filtered, integrated with one another and oriented – for this purpose, transformation was performed based on the adjustment point (measurement targets) to which the coordinates from tacheometric measurements were assigned. All calculations were performed in the Polish National Spatial Reference System 2000, as all surveying works during project implementation were carried out in this coordinate system. It is important to be able to compare different work results. It is also worth noting that the 2000 reference system has a projection distortion, which is why it has been locally modified by introducing a scale factor equal to 1. Thanks to this, there are no reproductive distortions. Finally, a point cloud of the southern part of the diaphragm wall on storey-1 was obtained (see Figure 5). Figure 5, in the bottom part, also shows a part of the wall on storeys-2/-3 – this is a point cloud obtained during the second measurement cycle (measurements in successive measurement cycles were oriented the same way).

The second measurement cycle was made on 30 June 2017 on storeys-1 and -2/-3 of the complex. Similarly as for the storey-1 in the first cycle, for the storeys-2/-3, measurement marks in the form of targets were arranged at the surveyed diaphragm wall and poles. Then, the location was selected for eight laser scanner stations and three tacheometer stations on storeys-2/-3. The observation data obtained as well as the point clouds were elaborated analogically to the first cycle. As a result, two point clouds comprising the entire diaphragm wall – on storeys-1 and -2/-3 were obtained (see Figure 5).

3 Results

3.1 TLS measurement results' analyses

The following chapter presents the analyses of measurement results from two independent measurement periods. In each of them, the survey geodetic network had different locations of measurement stations, but the same location of reference points. An important element

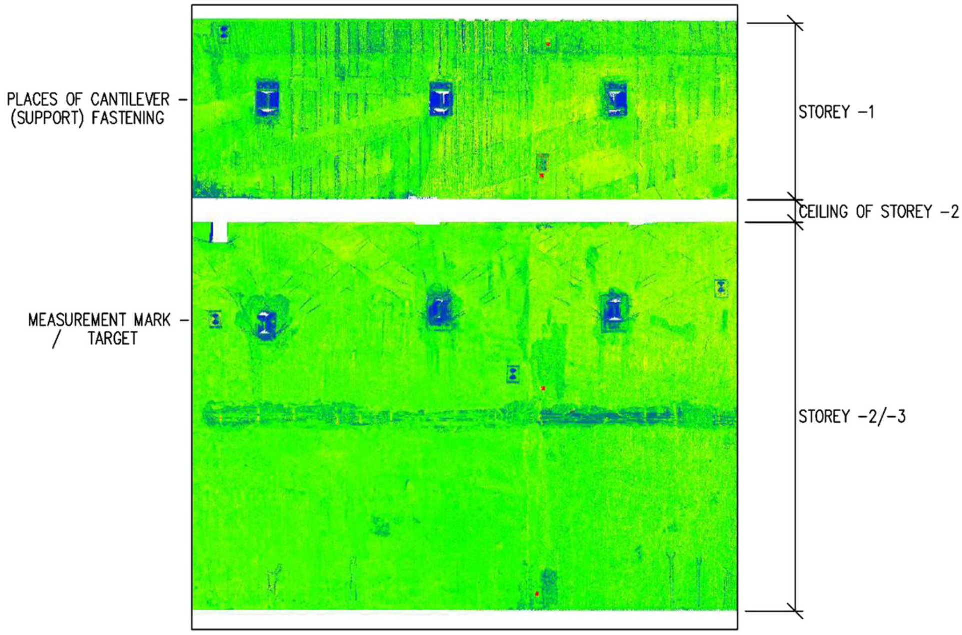


Figure 5: A part of the oriented point cloud obtained from scanning. The cloud is coloured as per registered values' intensity. Places of cantilever (support) fastening and measurement targets (marks) visible on the wall.

in the process of displacement and deformation analysis is in checking the stability of reference points (points marked in red in Figure 2b). The results verify the significance of the displacements of the reference points presented in Table 1.

As a result of independent processes of least squares alignment, the mean errors in determining the position of the points (in 3D space) did not exceed 2.5 mm.

In order to compare the precision of laser scanner measurements with classic angular and linear measurements, differences in the coordinates of the corresponding points in the scan and the rangefinder foils independently measured with a tacheometer were calculated. For this reason, well-mapping marks in the form of targets (see Figure 5) were additionally located next to the rangefinder foils at the measured diaphragm wall. The results obtained are presented in Table 2. The differences between the displacements obtained in measurements with the use of two different measurement techniques (tacheometry and TLS) are within a twofold error in the determination of these displacements (see Table 1). This positively verifies the use of cloud point analysis in surveying diaphragm walls.

Analysing the results presented in Table 2, one needs to account for the specifics of scanning laser measurements. Rangefinder foils commonly used in angular and linear control measurements of facilities are not proper marks for scanning. The reflective material used for the foil production, appropriate for the measurement of the distance, causes problems in precise identification of the location of the measured points in scans, both on the plane of the scanned surfaces and in the perpendicular direction (which can be seen in Figure 6 in the form of a blurred point cloud (red colour)).

Figure 6 shows the method of designation of the coordinates of control point 103 in the form of a reflective

Table 1: Results of verification of the significance of the displacements of the reference points

Point ID	d*X* [mm]	d*Y* [mm]	m_{dX} [mm]	m_{dY} [mm]	Significance < 2.5	
503	0.10	−0.10	0.72	0.85	0.14	0.12
504	0.60	−1.00	0.78	1.13	0.77	0.88
505	1.70	−0.10	0.86	0.86	1.98	0.12
506	1.30	0.60	0.71	0.71	1.84	0.85
507	−0.90	−0.60	0.64	0.71	1.41	0.85
512	−2.10	1.10	0.85	0.99	2.47	1.11

Table 2: List of differences in the coordinates of the points measured in cycles 1 and 2 on storey-1

Point ID		Difference in the coordinates from tacheometry (cycle 2 – cycle 1)			Difference in the coordinates from scanning (cycle 2 – cycle 1)			$dB_t - dB_s$ [m]
Reflective target	Mark	dX_t [m]	dY_t [m]	dB_t [m]	dX_s [m]	dY_s [m]	dB_s [m]	
1000		−0.0009	0.0000	−0.0008	−0.0010	0.0005	−0.0006	−0.0002
	102	—	—	—	−0.0042	−0.0005	−0.0038	
101		−0.0036	0.0007	−0.0026	−0.0015	0.0005	−0.0010	−0.0016
201		−0.0015	0.0000	−0.0013	0.0015	0.0000	0.0013	−0.0025
	108	—	—	—	−0.0007	−0.0001	−0.0006	
102		−0.0023	−0.0003	−0.0021	−0.0020	−0.0005	−0.0019	−0.0001
	120	—	—	—	−0.0019	−0.0007	−0.0020	
202		0.0003	−0.0013	−0.0005	−0.0010	0.0013	−0.0001	−0.0004
103		−0.0012	−0.0010	−0.0016	−0.0010	−0.0020	−0.0019	0.0004
203		−0.0010	−0.0013	−0.0016	0.0010	−0.0010	0.0003	−0.0018
	126	—	—	—	−0.0022	−0.0020	−0.0029	
1001		−0.0007	−0.0009	−0.0011	−0.0005	0.0005	−0.0001	−0.0009

foil stuck to the diaphragm wall surface. The location of the point, determined in the tacheometric measurement, is marked in green. The point cloud recorded while scanning was divided according to the registered intensity value (I) into either measurement background noise or points representing the true surface. The value of $I > 180$ was adopted as the division criterion, since it is the limit of twofold standard deviation for a normal distribution of intensity values. The point cloud noise in the perpendicular direction to the diaphragm wall axis does not exceed 0.003 m. In order to analyse the tacheometry and laser scanning results, the correspondence of the determined displacements in the normal direction towards the wall face (dB_t, dB_s) was analysed. The differential method of calculations was used. The location of the centre of the reflective foil in each scan was determined, based on the best least square linear fit in selected points representing the true surface (the blue points in Figure 6). The location of the centre of the foil was assumed, accounting for the normalized size of the mark.

The differences between the designated coordinates (see Table 2) are the result of varying accuracy of both measurements and the method of installation of the rangefinder foils that were affixed with a few-millimetre silicone layer. Due to the various nature of tacheometric data (discrete) and data from TLS (quasi-continuous) when comparing the results, the correspondence of the trends in displacements determined with both methods should be noted. In both cases, a lack of occurrence of significant displacements may be noted, which is in compliance with the forecast behaviour of the wall strengthened with cantilevers after uncovering the storey-1.

As the displacements of the reflective foil determined with use of laser scanning are approximated values, the determined differences in the coordinates of the nearest points signalled with scanning-dedicated targets (black and white sheets) are included in Table 2 (points id: 102, 108, 120). Figure 7 presents the arrangement of the points described in Table 2.

A multi-temporal survey of the facility allows for detection of the wall deformation during the execution of the successive stages of construction. The analysis of the point clouds registered in various periods enables tracing the measurement profile deformation arrangement throughout the height, and not only at a selected point. Figure 8 is an example presenting a part of a vertical section through point clouds from the two measurement cycles. The point clouds from both measurements are differentiated with colour. The figure shows that changes in the analysed cross-section occurred only in the selected parts. It should be noted that when performing measurements using the tacheometric method, the control points can be mounted in places where there is no deformation. Discrete information obtained in this way will not show actual changes. That is why the advantage of continuous information provided by TLS is so important.

3.2 Verification of the diaphragm wall construction project and the diaphragm wall behaviour forecast

Integration of the results of successive control measurements into the diaphragm wall design allows for fast control of the facility construction, identification of

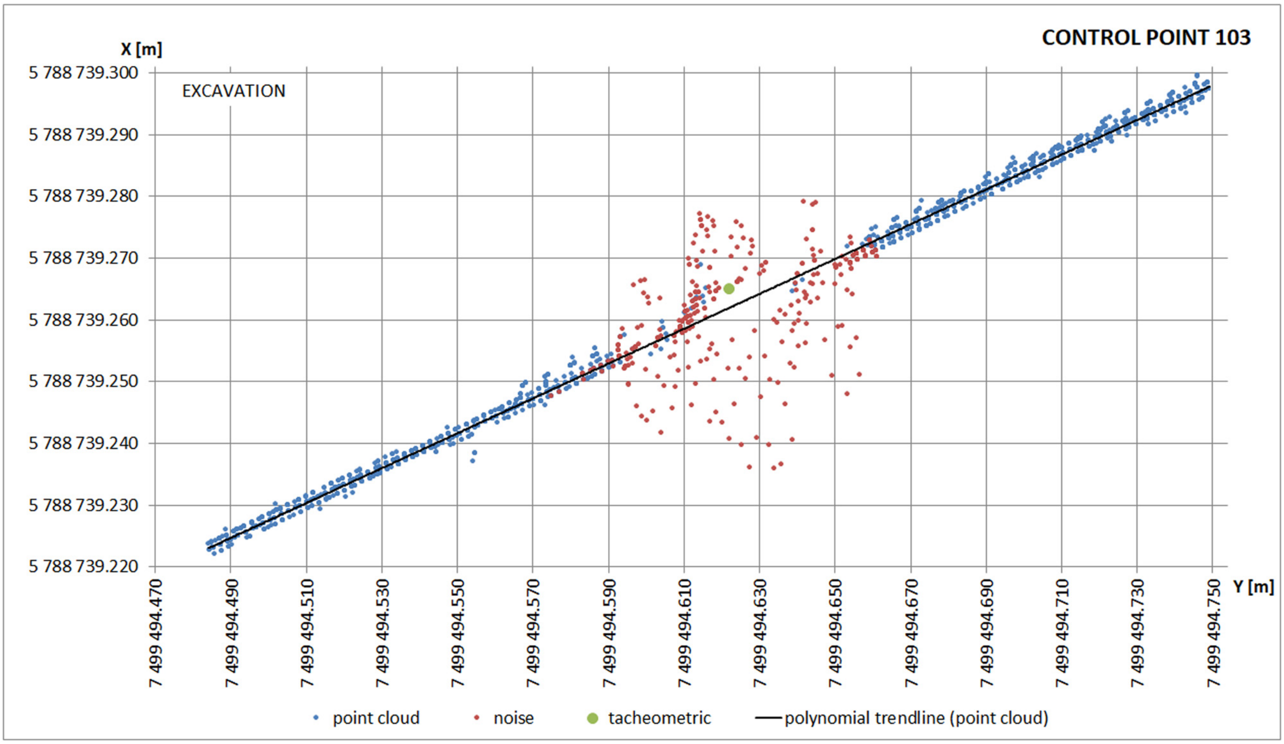


Figure 6: Cycle 1 – designation of the coordinates of profile 103 point. A view of a part of the diaphragm wall on the horizontal plane with the blurring of a part of the cloud depicting the reflective target of point 103.

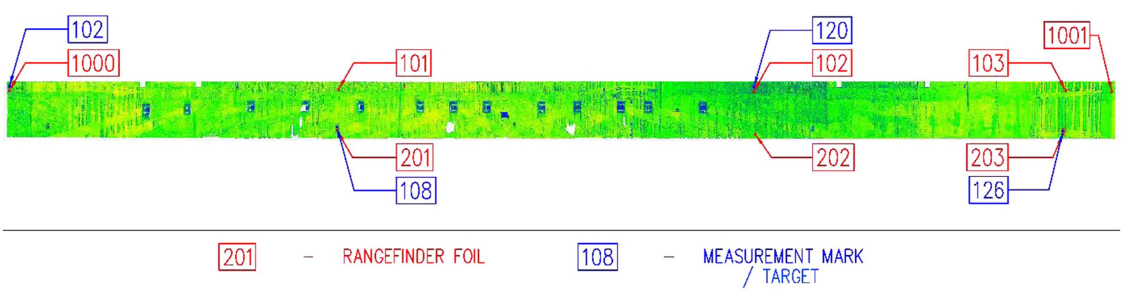


Figure 7: Location of the control points for which differences in the coordinates were determined (cycle 2 – cycle 1). Numerical data are included in Table 2.

discrepancies and problems as well as reactions of the construction site management or the investor in the form of: replacement of the design, extra security of the structure, use of other raw materials or finishing materials. In other words, this enables the implementation of 4D assumptions of the BIM system (or even more advanced ones).

During the trenching of the excavation and the performance of survey measurements, the authors of the article made an attempt to integrate a relevant part of the design with the TLS measurement results. The facility contractor – Warbud S.A. – was provided with information on an ongoing basis, which allowed for active management of construction works. Figure 9 presents point clouds from both measurement cycles, coloured as per the distance of a single point cloud from the designed course of the diaphragm wall.

In the central part of Figure 9. symmetrically in relation to the middle of the diaphragm wall, in places marked with arrows, significant deviations from the design, reaching 0.15 m, can be noticed. Diaphragm wall deflections while trenching the excavation may attest to the worse quality of the reinforcement or concrete used for the construction of this part. The wall design, without considering all geotechnical aspects having an impact on the behaviour of the wall, may be the reason for the

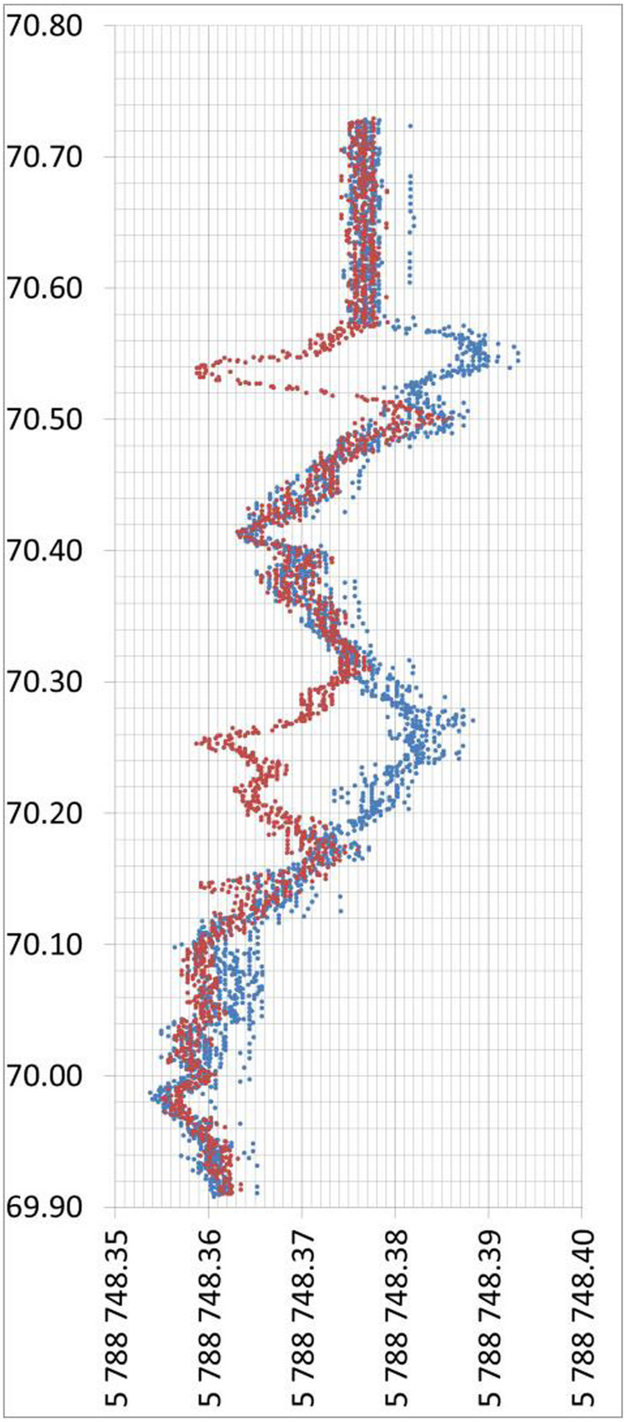


Figure 8: Vertical section of overlapping point clouds in the upper part control profile. Blue colour – cycle 1. Red colour – cycle 2. Distance units [m].

deflections. In the case of this facility, due to the proximity of the underground tunnels running parallel to the designed wall axis, failure to consider the impact of vibrations coming from underground trains running was a possible reason for the deformations.

Another example of using TLS point clouds is control of the execution of particular elements considering not only basic geometric features (such as location, length, width or height) but also the surface. The surface of diaphragm walls due to the technology of their construction is never a perfect reflection of the design. In many facilities, claddings and facades of prefabricated elements are made to complete underground storeys. TLS may be successfully used for the purpose of designing and supporting the execution thereof.

Figure 10 presents an extract of a draft illustrating verification of the course of the diaphragm wall surface at the height of 80 cm on storey-2. The discrepancy visible in the draft and a number of similar ones occurring at the length of ca. 30 m make a difference in the surface of ca. 1.7 m^2 in relation to the design. Local non-flatness of this kind is important when designing and choosing the finishing cladding.

4 Discussion

In the authors' opinion, despite a number of problems related to the performance of TLS control measurements of diaphragm walls while trenching the excavation with a top-down method, it is worthwhile to apply this method due to the quasi-continuous nature of the results in the form of point clouds and a possible full integration of the results into the structure design.

A negative impact of many external aspects may be limited by applying the following points:

1. performing a measurement plan – scanning preceded by a field interview and an analysis of the design documentation will allow for such a location of the instrument stands, which will assure performance of measurements at the maximum wall surface, despite a large number of construction elements such as poles, supports and formwork;
2. due to a relatively short measurement time at a single stand, measurements may be performed during the breaks in the staff work on the construction site – this will limit the impact of subsoil vibrations caused by the machines in operation on the measurement results;
3. arranging the points connecting the scans (e.g. in the form of targets) at various heights around the planned scanner stands. A higher number of points at structural elements (poles) will compensate for a lack of common points on the side of the excavation – blind spots;

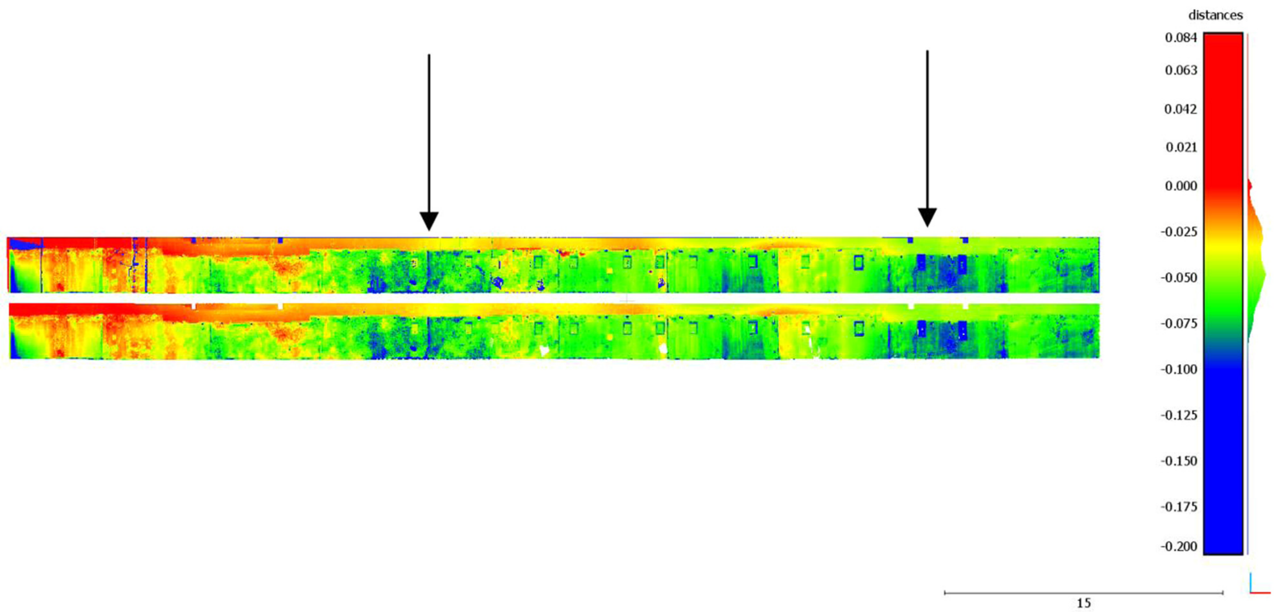


Figure 9: Distances of the clouds from the first (at the top) and the second cycles (at the bottom) from the designed course of the wall (units of horizontal scale [m], units of colour scale [m]).

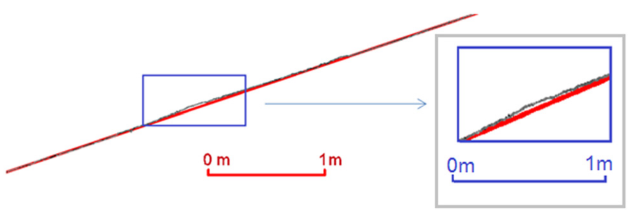


Figure 10: The area in which there is a discrepancy between the actual course of the wall (dotted line) and the design (red line) to a substantial degree.

4. during the analysis of wall deformation, an impact of possible subsoil contamination remaining after the excavation trenching should be considered – a method of wall cleaning tested by the authors is prior washing with high-pressure water washers (at least 6 h before the measurement);
5. in order to obtain high accuracy of point clouds, precise angular and linear measurements should be used for connecting the scans and providing georeferencing.

The most important advantages of applying the TLS technique in combination with tacheometric measurements for a survey of diaphragm walls include:

1. high accuracy of the point cloud comparable with the accuracy of angular and linear (tacheometric) measurements;
2. analysis of point clouds allows for the designation of quasi-continuous 2D deformation models enabling the performance of comprehensive geometric analyses;
3. possible implementation of BIM multi-dimensional models: 4D (*XYZ*, time), 5D (*XYZ*, time, costs);
4. easy identification of increased filtration areas, based on the registered values of intensity of laser radius reflection from the wall surface;
5. a relatively short time of performance of measurements;
6. possibility of performance of measurements with limited lighting, at night.

Integration of the information of various nature in BIM and the ease of implementation of changes, facilitating aspects such as an increase in control and safety of the project, a possible increase in the effectiveness of project works and a reduction of costs, also involves a risk of certain information chaos. Therefore, special attention should be paid to a high standard of documentation workflow. Yet, there are the relevant administration clauses that make the design legally binding. Unfortunately, the clauses, mainly in compliance with the Building Law applicable in Poland, are of analogous nature.

It should also be considered whether as of today the BIM is developed enough to comprise successive dimensions. In the publication [14], the successive levels of BIM implementation are distinguished. Zero level is a level at which the construction industry has stagnated for many years. Hardcopy documents, containing flat drawings, tables and descriptions, are the communication carriers in use. Only some information is stored in CAD files by project participants. The successive levels of

BIM implementation, assuming the project multi-dimensionality, require the implementation of relevant legislation changes.

References

[1] Burland JB, Baster J, Bell BC, Black WA, Donaldson PK, Doran DK, et al. Design and construction of deep basements including cut-and-cover structures. London: The Institution of Structural Engineers; 2004.

[2] Prószyński W, Woźniak M. Geodezyjny monitoring przemieszczeń obudowy wykopu i obiektów sasiadujących (doświadczenia z obiektu EUROPLEX w Warszawie) [Geodetic monitoring of displacement of the excavation casing and neighbouring facilities (experiences from the EUROPLEX facility in Warsaw)]. Przegląd Geodezyjny. 1998;70(12):13–8. (in Polish).

[3] Siemińska-Lewandowska A, Mitew-Czajewska M. Nowe wyzwania przy projektowaniu obiektów II linii metra w Warszawie [New challenges during designing facilities of Line 2 of Warsaw metro]. XII Seminar IBDIM – Geotechnika dla inżynierów, Głębokie wykopy 2013". [IBDIM – Geotechnics for engineers "Deep Excavations 2013"], Warsaw; 2013.

[4] Polish Standard: PN-EN 1997-1:2008 Eurocode 7. Part 1. Geotechnical design.

[5] Popielski P. Oddziaływanie głębokich posadowień na otoczenie w środowisku zurbanizowanym [The influence of deep foundations on urban environment]. Sci Work Wars Univ Technol Ser Environ Eng. 2012;61:3–168. (in Polish).

[6] Breymann H, Fuchsberger M, Schweiger HF. Deep open excavation in soft plastic ground in Salzburg, Austria. In: Mair RJ, editor. Geotechnical aspects of underground construction in soft ground. Proceedings of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground. Rotterdam; 1996. p. 69–74.

[7] Zaczek-Peplinska J, Kowalska ME. Terrestrial laser scanning in monitoring hydrotechnical objects. J Ecol Eng. 2016;17(4):120–8. doi: 10.12911/22998993/63887.

[8] Muszyński Z. Assessment of suitability of terrestrial laser scanning for determining horizontal displacements of cofferdam during modernization works on the Rędzin sluice. 14th International Multidisciplinary Scientific GeoConference SGEM 2014. Proceedings of SGEM2014 Conference. Vol. 2, Albena, Bulgaria: 2014. p. 81–8.

[9] Muszyński Z, Rybak J. Evaluation of terrestrial laser scanner accuracy in the control of hydrotechnical structures. Studia Geotechnica et Mechanica. 2017;39(4):45–57. doi: 10.1515/sgem-2017-0036.

[10] Wujanz D, Neitzel F, Hebel HP, Linke J, Busch W. Terrestrial radar and laser scanning for deformation monitoring: first steps towards assisted radar scanning. ISPRS Ann Photogramm Remote Sens Spat Inf Sci. 2013;II-5(W2):325–30. doi: 10.5194/isprsannals-II-5-W2-325-2013.

[11] Pawłowicz JA. Importance of Laser Scanning Resolution in the Process of Recreating the Architectural Details of Historical Buildings. IOP Conference Series: Materials Science and Engineering; 2017. p. 245. doi: 10.1088/1757-899X/245/5/052038.

[12] Daniotti B, Pavan A. Evolution of the Building Sector Due to Digitalization. BIM-Based Collaborative Building Process Management. Springer Tracts in Civil Engineering; 2020. p. 1–16. doi: 10.1007/978-3-030-32889-4.

[13] Frequently Asked Questions about the National BIM Standard – United States: What is a BIM, 2018. http://www.nationalbimstandard.org/faqs#faq1.

[14] Kasznia D, Magiera J, Wierzowiecki P. BIM w praktyce [BIM in practice]. Wydawnictwo Naukowe PWN. Warsaw: 2018. (in Polish).

[15] Randall T. Construction engineering requirements for integrating laser scanning technology and building information modeling. J Constr Eng Manag. 2011;137(10):797–805. doi: 10.1061/(ASCE)CO.1943-7862.0000322.

[16] Mennica Legacy Tower, 2018. https://www.mennica.com.pl/uslugi/nieruchomosci/mennica-legacy-tower.