

Application of Terrestrial Laser Scanning and Inclinometer for Comprehensive Monitoring of Deep Excavation

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ABSTRACT: The subject of the article is the observation of the displacements of the diaphragm wall, which protects the deep excavation during its digging and exploitation. The research object was located in a compact urban development, in the vicinity of the city moat and a communication tunnel. The typical scope of trench protection is limited to measuring the horizontal displacements of the control points located on the crown of the wall with the use of electronic total stations. Geodetic measurements allow to detect horizontal displacements in an external reference system which is independent of the controlled structure. The use of terrestrial laser scanning (TLS) significantly increases the detailed control of the geometric condition of the deep excavation lining. Instead of a discrete measurement (carried out at selected control points), it is possible to obtain a 3D model of the entire excavated retaining structure. By assigning appropriate georeferences to point clouds from subsequent measurement periods with inclinometer measurements, the authors determined the values of wall displacements and building inclination, and used point clouds to detect leaks and wall surface moisture.

KEYWORDS: diaphragm wall, displacement monitoring, LiDAR, point cloud, leaks identification.

1 INTRODUCTION

The impact of deep excavations on the surrounding environment may be divided into two groups (Zaczek-Peplinska *et al.*, 2020):

- physical (resulting from soil mechanics and the interaction of the soil with the retaining structure,
- process (related to the adopted engineering solutions and quality of work execution).

The impact of deep excavations on the surrounding environment is significant, therefore, it is necessary to use various monitoring tools. These include direct monitoring of the excavation protection (leaks), displacements and deformation, and monitoring of surrounding buildings and structures. Ensuring security is possible thanks to advanced geotechnical analysis and selection of excavations protection technology and complementary monitoring methods.

One of the common applications of geodetic methods in relation to geotechnical structures is the measurement of displacements and deformations soil-structure systems. The widespread techniques and detailed descriptions of these studies are published (Grzempowski *et al.*, 2020), (Oskouie, Becerik-Gerber and Soibelman, 2016). The main loads on the retaining structure are the active pressures and resistances of the earth (*EN 1997-1 Eurocode 7: Geotechnical Design—Part 1: General Rules*, 2009), the values of which will change during the excavation progress. The final values of the pressures are established after the target excavation depth is reached and the displacements of the retaining structure have stabilized. For this reason, it is necessary to conduct ongoing measurements of the displacements of the excavation protection. In particular, passive pressure is mobilized below the bottom of the excavation, and this is an impact dependent on the displacement of the retaining structure towards the ground. However, conventional monitoring systems like the extensometers, inclinometer measure the variations of strain and displacement at discrete locations at which they are installed in diaphragm wall. The typical scope of trench protection is limited to measuring the horizontal displacements of the control points located on the crown of the wall with the use of electronic total

stations. Geodetic measurements allow to detect horizontal displacements in an external reference system which is independent of the controlled structure. These displacements are controlled on the excavated surface of the retaining structure. By leveraging the advantages of the presented measurement methods, the displacements of the retaining structure are observed both on visible surfaces and at inside mounted inclinometer casing. This creates a synergy between two measurement methods, which cover different measurement ranges within a deep excavation. The possibilities of using the data acquired, among others, for the indication, spatial surface and buildings deformation analyses and assessment of the wall execution compliance with the design are presented.

2 RESEARCH OBJECT

Diaphragm walls are deep extended walls through granular or cohesive soils in shallow water table areas. The concept of vertical reinforced-concrete panels is both technically effective and economically justified also in order to reduce large loadings transmitted through the ground (Lei *et al.*, 2019).

Diaphragm walls provide high rigidity of excavation protection and their specific rough surface is beneficial for modifying earth pressure and soil resistance. Studies have been conducted to measure roughness in geotechnical engineering. The shear strength between soil and structure is also affected by the roughness. Studies on the correlation between roughness and the bearing capacity of retaining wall such as piles have been also conducted (Tehrani *et al.*, 2016), (Wyjadłowski, Muszyński and Kujawa, 2021). However, the construction of the diaphragm walls is always accompanied with a lot of difficulties and problems which are based mainly on how to estimate the deformation of the trench sides in the deepening phase (Han *et al.*, 2013). These measurements enable evaluation of the size and range of excavation impact on surrounding structures (Rybak *et al.*, 2018), as well as displacements of excavation supporting system – usually its top. The construction site of an office building was located in Wrocław, Poland. The city is situated on The Silesian Lowland. It spreads from the southeast to the northwest, along the glacial valleys of the Oder River, which is filled with alluvial sediments of Pleistocene and Holocene, mostly sand and gravel (Kabała *et*

al., 2015). For decades, the area of the city has undergone intensive processes of urbanization, development of processing industry, and damage from military conflicts and reconstruction afterwards and two so-called thousand-year floods in 1903 and 1997. These activities became the reason for changes in the natural environment, especially in the subsoil. The anthropogenic changes take place on the surface of the terrain where they have impact on the civil structures. A diaphragm wall with thickness of 80 cm was installed at the excavated depth ranged to 12 m. The bottom of the wall was sunk 5.5 m below the excavation depth in cohesive soils. The planned underground part of the building will include three levels of a car park. The geotechnical cross-section with a view of the excavation protection is shown in Figure 1, where “Mg” is anthropogenic soil, “MSa” is medium sand, “gr” is gravel, “grSa” is sandy gravel, and “saCl” is sandy clay. The ground is composed of anthropogenic soils and sedimentary soils. After the excavation has been made, slurry wall surfaces in non-cohesive, saturated soil are accessible. The geotechnical conditions are favourable, because the slurry wall sinking in low permeable cohesive soils prevents the inflow of groundwater into the excavation.

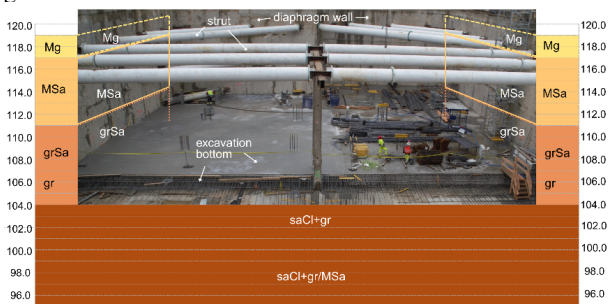


Figure 1. Diaphragm walls supported by struts - the cross-section of the excavation and geotechnical conditions.



Figure 2. Concrete diaphragm wall constructed adjacent to the existing building.

Displacements the deep excavation support are monitored to ensure that the structure meets its load-bearing and serviceability limit states. The technical condition and hazard identification for structures adjacent to the deep excavation are not fully understood, and despite the safety of the excavation support, the impact on the surrounding area may be detrimental. Structures within dense urban development have undergone construction processes: reconstruction and consequent changes

to their original static patterns due to disruption of the original continuous development. Depending on the size of the predicted ground displacements and the technical condition of buildings, it is often necessary to protect or strengthen their structural elements (Dmochowski and Szolomicki, 2021). There have been studies concerning the influence of foundation deformations on the cracking of ceramic walls (Kania, Derkach and Nowak, 2021). It can be concluded from the first research analyses concerning the operation of masonry walls on flexible supports that in order to protect them from cracking, the ratio of deflection of the supporting structure to its span should not exceed 1/2000, and bending tensile strength of the wall should not be lower than 0.21 MPa (Meyerhof, 1953). The monitored building from 1890 has been used intensively as a education facility for 130 years and was subjected to impacts that can be described as exceptional: changes and losses in adjacent dense development, flood effects and influences of the investment environment. During the construction phase, it was exposed to prolonged vibrations due to the diaphragm wall excavation technique used. Despite the high rigidity of the excavation protection, (Fig. 2) some damage occurred to the masonry structures of the adjacent buildings.

3 MATERIALS AND METHODS

Geodetic measurements allow for monitoring vertical and horizontal displacements of structures determined in an external reference system, unrelated to the construction site or the structure itself. Vertical displacements are determined based on measurements made using precise geometric levelling. Horizontal displacements are most often determined based on precise tachymetric measurements made using robotic total stations. Geodetic monitoring most often covers selected, characteristic locations of structures that have benchmarks, retroreflective targets or geodetic prisms installed. Terrestrial laser scanning is increasingly used to monitor displacements and fractures (Chen, Walske and Davies, 2018). Its advantage is that the measurement covers the entire surface of the object, not selected points of the structure, which are signalled by geodetic signs. Depending on the type of scanner used, for each measured point it is possible to obtain, in addition to the X, Y, Z coordinates, additional information in the form of RGB colour, laser beam reflection intensity, amplitude, or standard deviation of the reflected laser pulse. A significant limitation of geodetic measurement methods is a possibility of monitoring only exposed elements of the diaphragm wall structure. The solution to this problem is a use of inclinometric measurements, which allow determining the axis of deformation of the retaining structure along the entire length of this structure, i.e. from the crown of the diaphragm wall to its base. The points measured in the inclinometric tube are located inside the diaphragm wall, therefore the inclinometric measurement also covers that part of the diaphragm wall that is below the current bottom of the excavation (inaccessible for geodetic measurements). However, it should be remembered that the inclinometric measurement is a relative measurement, which can sometimes have serious consequences. The considered points on the obtained deformed axis are not related to an external reference system, hence the inclinometric measurement does not provide information about potential displacement of the retaining structure as a rigid body (in the sense of the entire structure).

4 DIAPHRAGM WALL SURFACE INVESTIGATION

Laser scanning of the entire construction site was performed with a Riegl VZ-400i pulse scanner from about 30 positions (Figure 3). Panoramic scan with a resolution of 20 mdeg, scan

of visible tie points signalled by reflective targets, and series of wide-angle photos from the integrated camera were performed at each scanner position. The final combination of filtered point clouds was carried out by mutual alignment of the common surfaces also considering the tie points. Afterwards, the merged point cloud from all scanner positions was fitted to the target local coordinate system based on the known coordinates of the tie points. The mean error of georeferencing process did not exceed 2.5 mm for all measurements periods.

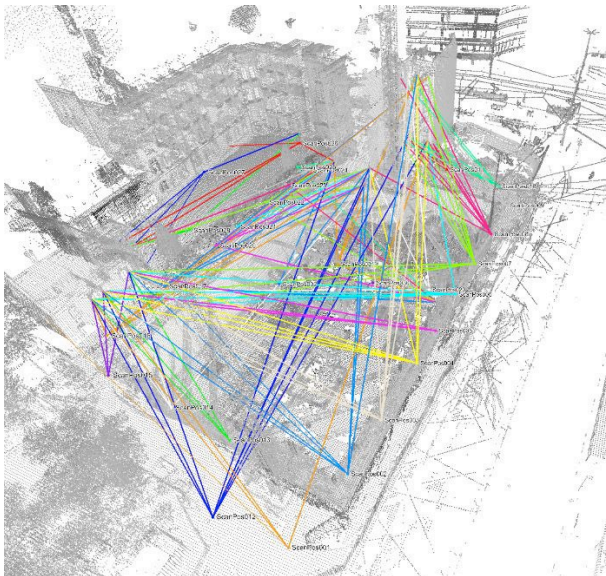


Figure 3. Mutual alignment of point clouds using the cloud-to-cloud method with georeferencing based on detected reflective targets.

In Figure 3 for each scanner position, the lines of sight are shown in a different colour. The primary product of laser scanning is the point cloud. Each measured point has xyz coordinates and RGB color obtained from photos. In addition, the intensity parameter is recorded, which determines the strength of the laser signal after reflection from the measured object. Some terrestrial laser scanners, which are derived from technological solutions used in airborne scanners, can record additional parameters for each point describing the features of the reflected laser pulse. An example is the Riegl VZ-400i scanner used in this research, which records the following parameters: reflectance, amplitude, standard deviation, reflection number and GPS time. The reflectance parameter is particularly sensitive to moisture on the surface from which the laser beam is reflected. In the case of laser scanning of diaphragm wall surfaces, this feature can be used to detect various types of leaks. In order to obtain adequate leak detection efficiency, it is necessary to perform a statistical analysis of the variability of this parameter for a specific object. For the analyzed diaphragm wall, several damp places and a concrete surface without leaks were selected in several representative places. The value of the reflectance parameter for a damp diaphragm wall ranged from -13 to -6 dB (Fig. 4), while for a dry surface it ranged from -5 to -1 dB (Fig. 5). After analyzing the distribution for leak detection, it was decided to adopt a limit value of -7 dB.

The classification of the point cloud on the basis of the adopted limit value of the reflectance parameter made it possible to search for damp areas, examples of which are presented in Figure 6. Visual inspection of leaks is possible in areas accessible for inspection and with good lighting of the diaphragm wall. In low light or artificial lighting used at night, visual leak detection may be impossible (Fig. 7a). Laser

scanning measurements can be performed regardless of lighting conditions.

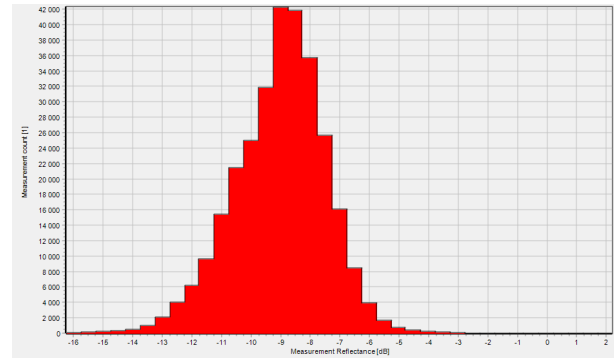


Figure 4. Histogram of the reflectance value distribution for a damp diaphragm wall.

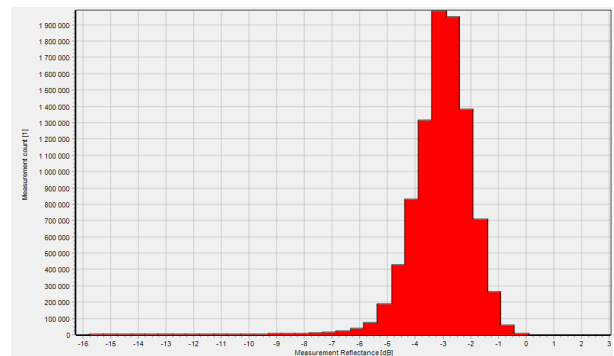
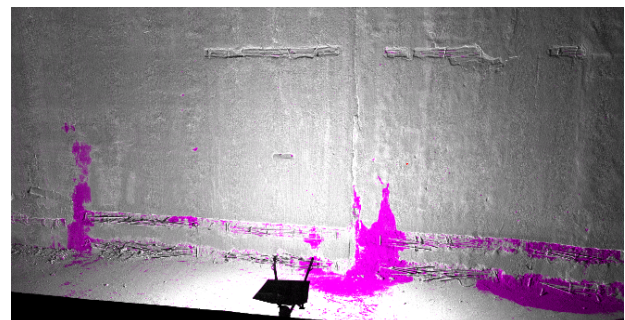
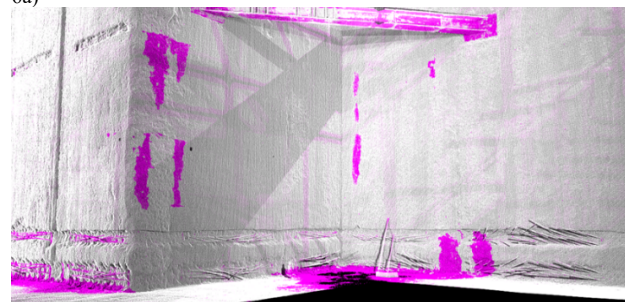


Figure 5. Histogram of the reflectance value distribution for a diaphragm wall without leaks.



6a)



6b)

Figure 6. Point cloud view with highlighted areas (purple color) of the diaphragm wall indicating moisture:

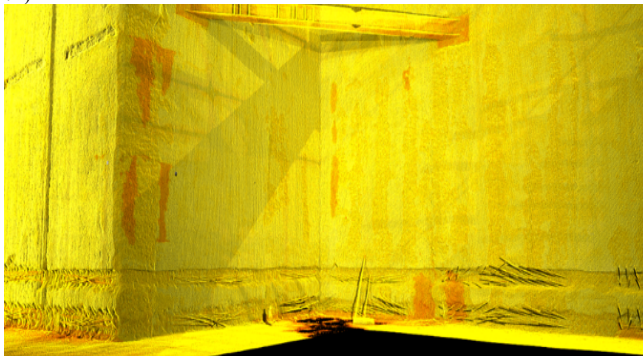
- a) connection zone of the diaphragm wall reinforcement with the foundation slab
- b) vertical leaks at the connections of technological segments.

The obtained reflectance parameter results can be visualized in different colors (Figs. 7b). It is important to remember that changes in the reflectance parameter value depend not only on moisture but also on other factors, such as the material from which the scanned object is made. An example is the steel strut

shown in Figure 6b. A solution to this problem could be a preliminary classification of the point cloud, separating the concrete surface of the diaphragm wall from the steel elements based on the shape and topology of the scanned elements.



7a)



7b)

Figure 7. a) Point cloud view in RGB colors (photos taken under artificial lighting of the trench), b) Visualization of reflectance parameters in orange color.

In summary, surface moisture value, leak detection are essential to allow construction work to proceed within the excavation, to ensure the durability of the diaphragm wall, and to avoid corrosion of the wall reinforcement and aesthetic defects. Regularly repairing leaks during the construction phase prevents them from developing during the facility's intended use.

5 TOTAL STATION MEASUREMENTS

A network of geodetic points was established on the construction site and its surroundings. The network consisted of nine reference points, five instrument stations, and more than 40 tie points. Measurements were performed with a robotic total station with angular accuracy 2" and distance accuracy 2 mm + 2 ppm in reflector mode. Each point was measured in at least two series. The angular-linear observations were adjusted with the least squares method in the adopted local reference frame. After adjustment, the mean square error of point position was equal to 2.56 mm, and did not exceed 3.9 mm for the worst determined point from all measurement periods. The apparent trend of different displacements between the lower and upper measurement points, see Fig. 8, was confirmed by the development of cracks in the building's masonry structure, see Figure 9. The direction of displacement of the external masonry walls was confirmed by the development of cracks on the external and internal walls.

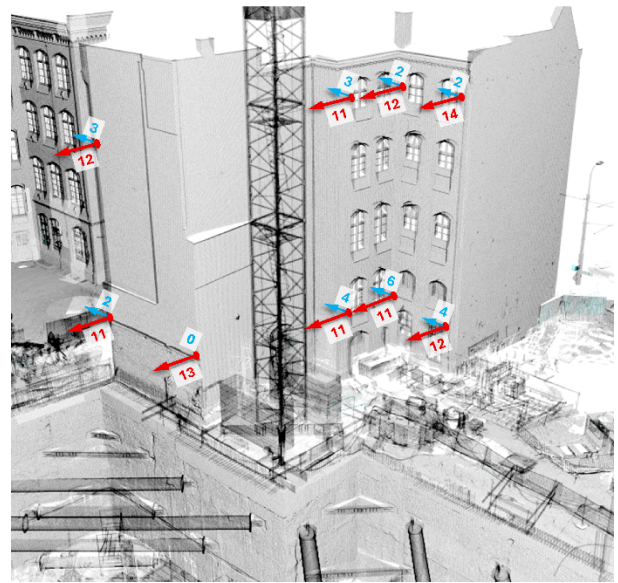


Figure 8. Permanent Building Displacements based on Total Station Measurements.



Figure 9. Characteristic pattern of damage to the building walls near the excavation

6 INCLINOMETRIC MEASUREMENTS

The inclinometers are widely used to monitor and deformation of geotechnical construction, which help indicate the development of sliding surfaces and understand the stability condition of landslides (Massey, Petley and McSaveney, 2013) and excavations (Gorska K. and Wyjadłowski M., 2015). The advantage of inclinometric measurement is that it allows obtaining information about the displacements and shape of the retaining structure axis also below the bottom of the excavation, where geodetic measurement technologies do not reach. However, traditional inclinometers need manual measurement at each depth which has low efficiency and provide only local data with the risk of missing critical points (Damiano *et al.*, 2017). Principles of inclinometer configuration and operation are presented in work (<http://www.slopeindicator.com>, no date; Stark and Choi, 2008). As a retaining wall or landslide moves, the vertical casing moves in the resultant direction of displacement. Comparing the verticality of the casing with the shape in subsequent measurements over time provides insight into the magnitude, rate, direction, depth and type of retaining wall movement (Stark and Choi, 2008). In addition, when the inclinometer is subject to large deformation, the inclinometer probe cannot be lowered down deeply into a borehole to record displacement. Due to existing problems, the application of traditional inclinometer is greatly limited for long-term

deformation of retaining wall monitoring. The precision of inclinometer measurement is limited both by the sensitivity of the inclinometer probe and by the reading operations that require successive readings with the same orientation of the instrument at the same depth in the casing. In the examined excavation, the diaphragm wall extends up to 8.0 m below the excavation bottom, meaning that its displacements are only observed over approximately 60% of the surface; observation of the state and displacements for the remaining surface is unavailable using surveying methods. Furthermore, the existing building with a basement is partially located within the excavation boundary, see Figure 2, Figure 8. The geodetic and inclinometric measurements were synchronized so that they were performed five times, during the achievement of subsequent stages of excavation deepening, installation of struts and progress of subsequent reinforced concrete works on the underground floors of the building. The displacement measurements of the diaphragm wall were taken during the excavation deepening until the target depth was reached. The presented graphs of the deformed axis show the increase in displacements in the period from August (measurement 0) to December (measurement 5). The development of the results of inclinometric measurements assuming the wall was fixed at its base as shown in Figure 10a and the displacements were corrected by the value of geodetic measurement at the top of the inclinometer tube (as shown in Figure 10b.).

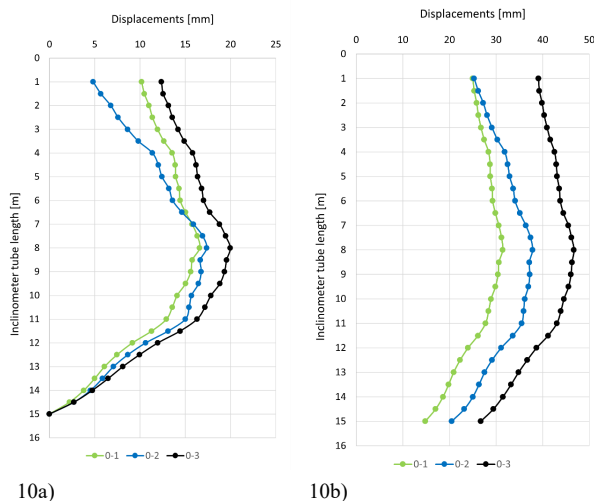


Figure 10. a) Displacements of diaphragm wall assuming the wall is fixed and the displacements in the base are zero, b) Displacements of diaphragm wall taking into account the possibility of wall base displacements obtained from geodetic measurement

Subsequent casing inclination readings are taken as the probe is gradually raised, usually at intervals of 0.5 m, to the top of the casing in which order the displacements are calculated. Measurement results are then processed with dedicated software. The disadvantage of the software is that it assumes that the displacements of the casing in the base are zero. The original method used is to assume a fix displacement of the top obtained from geodetic measurements and to calculate displacements at the next lower ordinates corresponding to the inclinometer readings based on their inclinations. The Figure 10 show comparative results for the three tested inclinometer casings, each casing marked with colors.

7 CONCLUSIONS

The synergy of complementary measurements is presented, among other things, for the analysis of spatial deformations of retaining structures and surrounding buildings. Instead of limited discrete measurements (performed at selected control

points), it is possible to obtain a 3D model of the excavation and its surroundings. By appropriately georeferencing point clouds from individual measurement periods, the authors determined displacement values and used the point clouds to detect wall surface moisture and building displacements, which are confirmed by developing cracks. The resulting displacement curve of the inclinometer tube takes into account the stiffness of the reinforced concrete diaphragm wall and displacements below the excavation bottom. Displacements of the wall below the excavation bottom are particularly important because they allow for the assessment of whether limiting passive earth pressure or lower values of resting earth pressure have been mobilized. This provides a reliable verification of the design assumptions for the retaining structure.

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