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

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**Abstract**

The article concerns comprehensive monitoring of the displacements of the diaphragm wall, which protects the deep excavation. The research object was located in a compact urban development, in the vicinity of the city moat and a communication tunnel. The typical monitoring is limited to measuring the control points located on the crown of the wall with the use of total stations. Geodetic measurements allow to detect displacements in an external reference system. However, the limitation is caused by the ability to measure the excavated parts of the retaining structure only. The application of an inclinometric technique allows to determine the displacements of the diaphragm wall also below the bottom of the excavation. Integration of these techniques allows to obtain the results of the inclinometer in an external reference system. A use of a terrestrial laser scanning significantly increases detailed control of the geometric condition of the deep excavation lining and gives a possibility to obtain a 3D model of the retaining structure. Giving an appropriate georeference to point clouds from individual measurement periods, the authors determined the displacement values and used the point clouds to detect the humidity of the wall surface. It allowed for the identification of leaks. Based on the integrated results of inclinometric measurements and the point cloud, the authors determined the curvature of the diaphragm wall, which is the basis for estimating the bending moments in the structure. Limiting the values of bending moments allows to control the width of cracks in the concrete.

***Keywords***: displacement monitoring, total station, inclinometer, laser scanning, diaphragm wall

## 1 Introduction

High prices of building plots in urban areas and limited space that can be used for development increase the number of storeys of newly constructed buildings. The law requires the provision of an appropriate number of parking spaces, which are usually designed as multi-storey underground car parks. These factors mean that construction projects more and more often include deep excavations in dense urban areas. These often are areas under the protection of the conservator of monuments, having a high historical and cultural value. In many instances, an additional difficulty is proximity of rivers, communication tunnels and dense urban technical infrastructure. Conducting deep earthworks is a big challenge for both the designer and the contractor of construction works. Geotechnical reconnaissance of the ground and knowledge of the groundwater level are of great importance. Artificial drainage of the construction site can lead to a loss of stability of neighbouring facilities. A support of a deep excavation should withstand the pressure of the soil surrounding the excavation and protect the adjacent buildings from damage. Most often these are cracks in walls, foundation subsidence or even construction failures. There is a risk of damage to the transmission networks located in the vicinity of the excavation. Unsealed gas installations can be extremely dangerous. Damage to transport infrastructure, especially railway or tram tracks, can also have dangerous consequences. Vibrations are also important, as they may occur both at the stage of lining a deep excavation and later, during further construction works. In order to ensure safe construction works and minimize the adverse impact of excavation on objects located in the vicinity of the construction site, it is necessary to skilfully implement comprehensive monitoring combining geodetic and physical techniques.

## 2 Monitoring methods

Geodetic measurements allow for monitoring vertical and horizontal displacements of geotechnical 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 (e.g. Feng, 2012; Pfeifer et al., 2007). 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. In order to use laser scanning to determine displacements in an external reference system, it is necessary to assign the point clouds an appropriate georeference. This is usually done by using reflective targets, which have current coordinates determined for each measurement period based on precise tachymetric measurements. 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). In particular, displacement of the crown of the retaining wall, which is important from the point of view of ensuring safety, is not determined here. The above-mentioned measurement techniques (geodetic and inclinometric measurements) should be combined, to achieve a synergy effect that eliminates their limitations. Adding laser scanning results allows the creation of 3D models of the diaphragm wall at individual stages of its construction and operation. By comparing models from different measurement periods, it is possible to determine displacements and deformations in a spatial, not just point, perspective. 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. These additional attributes extend the range of possible analyses. One of them may be detection of leaks in the diaphragm wall based on the reflectance parameter. Concrete is a porous material. The diaphragm wall is formed in difficult conditions, without the possibility of visual control, and the concrete mix has liquid consistency that allows for laying in the diaphragm using the "contractor" method. Experience has shown that properly designed and made concrete is usually sufficiently tight. The (EN 1538, 2015) standard states that it can be expected that diaphragm walls will not be completely watertight, as leaks may occur at the joints, at the recesses, or through the wall material. The joints of the sections are usually tight thanks to the built-in seal or a coating of filter sediment remaining from the suspension, but they do not guarantee perfect tightness. A favourable circumstance is a fact that the conditions of forming the walls in the ground environment practically eliminate shrinkage of the concrete of the walls. The height of the water pressure outside the walls has a significant impact on the tightness. Leaks may occur at the open corners of the walls and at the contact of the concrete at the top of the wall with the ring beam or other parts of the structure made in formwork. Particular attention should be paid to the connection of the wall with the foundation slab (Figure 1). Leaks may also occur as a result of excessive cracking of the wall due to overloading. The wall should be designed to maintain the permissible crack opening in accordance with the (Eurocode 2, 2006), usually 0.3 mm. If the conditions of the appropriate class are not met, injections are used, which are part of the technological process (Figure 2). Laser scanning can be used to detect leaks, which are characterized by a change in humidity and colour in hard-to-reach places.

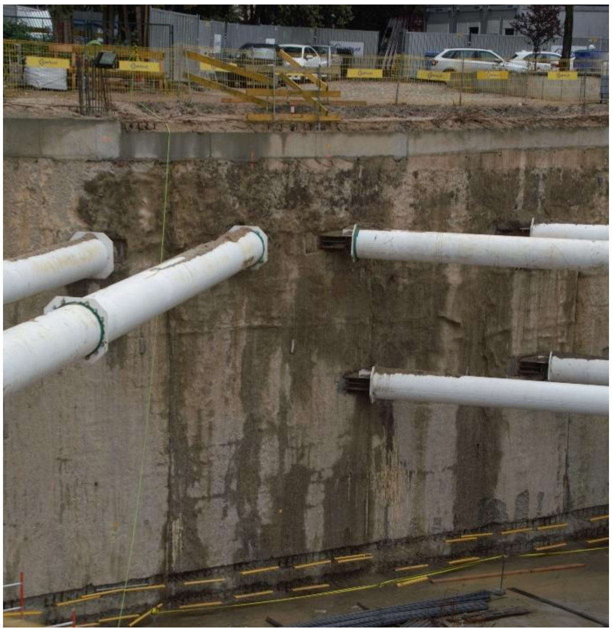

Figure 1. Typical leaks on the wall surface

Figure 2. Sealing the joints of wall segments by injection

# 3 Comprehensive monitoring

## 3.1 Object of research

The construction site of an office building was located in Wrocław, Poland. The city is situated on The Silesian Lowland. There is a vast plain with little diversity of relief. 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, a constant influx of people, development of processing industry, and damage from military conflicts and reconstruction afterwards. 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. Diaphragm walls are mainly designed and installed at recent excavation works in urban area because of some benefits such as high stiffness of the walls and reducing of construction time (Mitew-Czajewska et al., 2008). Figure 3 shows the considered excavation work site using diaphragm walls supported by struts system. 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.

Figure 3. Construction site - diaphragm walls and struts during earthworks

The main loads on the retaining structure are the pressures and resistances of the earth (Eurocode 7, 2008; Valsson, 2011), the values of which will change during the excavation. 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.

## 3.2 Geotechnical conditions

A geotechnical cross-section of the excavation site is presented in Figure 4, 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.

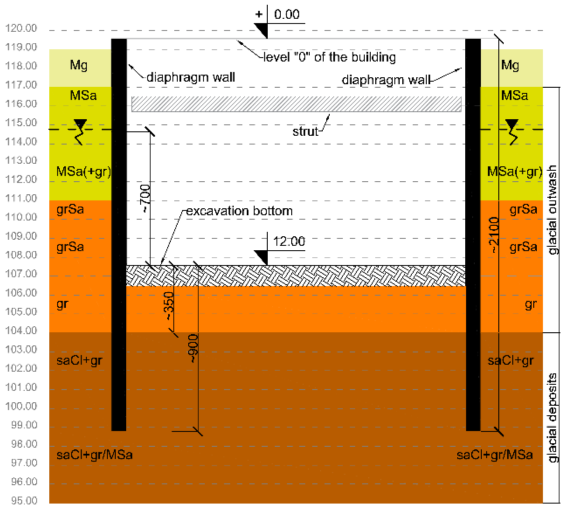


Figure 4. Diaphragm walls supported by struts - the cross-section of the excavation and geotechnical conditions

### 3.3 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: 0 - August, 1 - September, 2 - October and 3 - December.

### 3.4 Inclinometric measurements

The inclinometer measurements were carried out with an inclinometer system, which consists of an inclinometer probe, a dummy probe, an inclinometer cable and a data logger. The inclinometer probe, in the form of a steel beam with two sets of wheels, is equipped with a measuring device (Figure 5). It is lowered into the exploration hole on the inclinometer cable. The readings are recorded by the data logger. It allows wireless operation in the field, as well as previewing displacement graphs while the equipment is still on the measurement site. The displacement measurement method is based on measuring the inclination angle of the inclinometer probe form vertical direction. The measurements are performed on a stable level, which is enabled by copper rings crimped onto the cable (Figure 6). Each measurement cycle starts from the zero measurement. It should be performer directly after preparing the exploration hole, with the aim of determining its original shape and orientation. Then successive measurements are carried out at time intervals depending on work progress on the building site. Each measurement should be started from the "1st" direction and then continued clockwise. Measurement results are then processed with dedicated INCLI2 software (Incli2, 2006). This program allows the most common systematic errors to be corrected. There are four types of systematic errors: bias-shift, sensitivity drift, rotation error and depth positioning error. For well experienced users identification and quantification is very easy. The bias-shift error is a small error within one data set and is caused by a shift in sensor calibration value between opposite traverses. The combination of casing inclination and sensor axis alignment shift produces rotation error. It is produced when the casing has been installed with an inclination in the cross-axis and occurs as a small shift in probe or sensor alignment. When a significant casing inclination and vertical placement error occurs we should take into account depth-positioning error. The most common causes are change in probe depth or shortening of the casing. Those three errors can be easily corrected in the software. The sensitivity error needs reparation and calibration of the probe. Software for determining the deformed axis assume that the base of the retaining wall is fixed to the horizontal displacement. This assumption is not correct in all cases, hence forms of the deformed axis are created that deviate from its actual shape.

Figure 5. Inclinometric measurement system

Figure 6. Inclinometric measuring system at the measuring station

### 3.5 Terrestrial laser scanning

Laser scanning of the entire construction site was performed with a Riegl VZ-400i pulse scanner from about 30 positions (Figure 7).

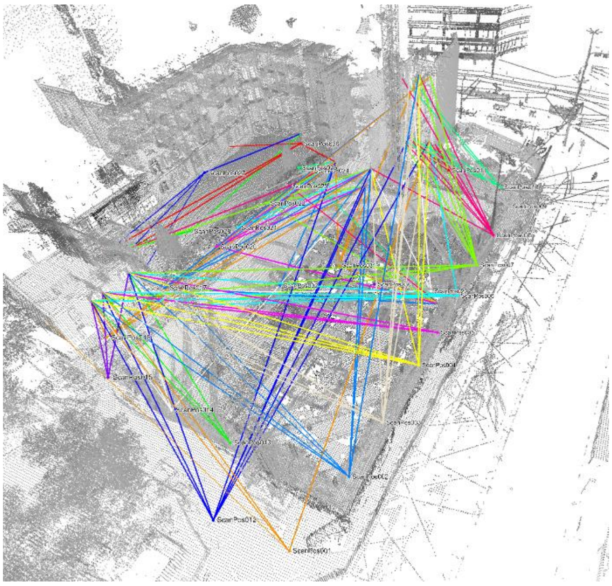

Figure 7. Mutual alignment of point clouds using the cloud-to-cloud method with georeferencing based on detected reflective targets. For each scanner position, the lines of sight are shown in a different colour

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.

## 4 Results

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 3). The development of the results of inclinometric measurements assuming the wall was fixed at its base as shown in Figure 8 and the displacements were corrected by the value of geodetic measurement at the top of the inclinometer tube (as shown in Figure 9.

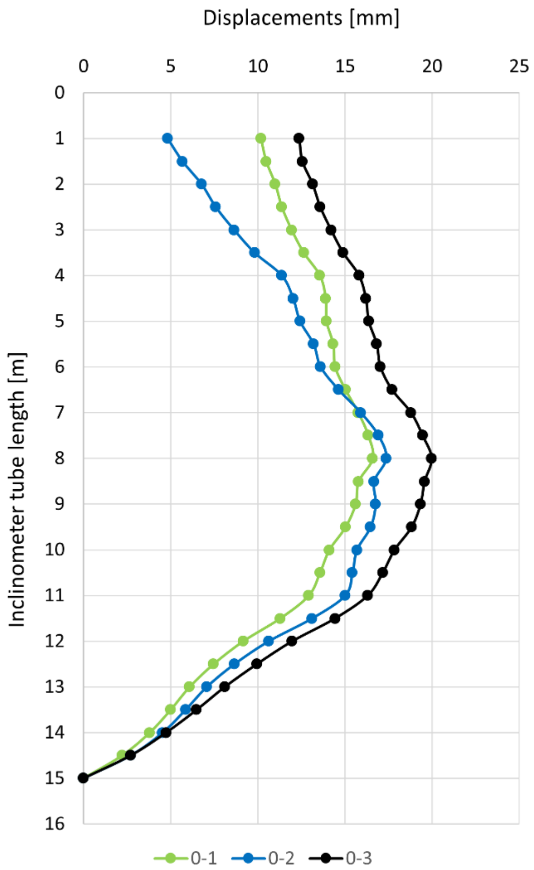


Figure 8. Displacements of diaphragm wall assuming the wall is fixed and the displacements in the base are zero

The result of detecting wet areas suggesting leaks in the diaphragm wall based on changes in the reflectance parameter in the point cloud is presented in Figure 10.

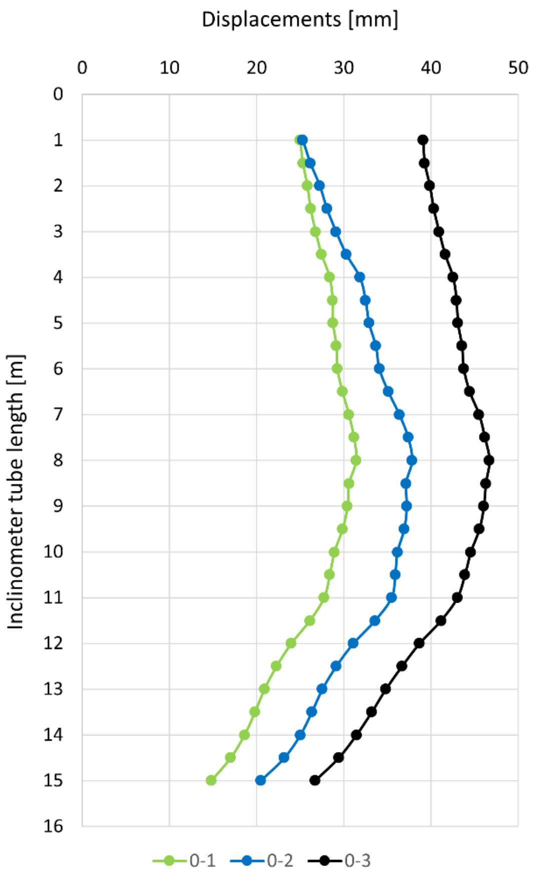


Figure 9. Displacements of diaphragm wall taking into account the possibility of wall base displacements obtained from geodetic meas.

Figure 10. View of the diaphragm wall with leaks: point cloud coloured from photos (RGB) at the top; point cloud (reflectance view) at the bottom

# 5 Conclusions

The assumption of the wall being fixed at the base leads to an underestimation of the observed displacements in the wall crown on the basis of inclinometric measurements. In Figure 8 an unrealistic change of the deformed axes was obtained for 0-1 and 0-2 periods, with a visible intersection point of these axes. This means a reduction in the displacement of the wall crown and is inconsistent with the geodetic measurement, where the displacement of the crown was constant. The obtained displacements of the retaining wall below the bottom of the excavation indicate a change in the type of resting pressure to intermediate and passive pressure. A gentler curvature of the deformed axis (Figure 9) indicates lower values of bending moments in the diaphragm wall. The wall should be designed to maintain the permissible crack spacing in accordance with (Eurocode 2, 2006), usually 0.3 mm. This requirement is easier to meet in the case of a larger radius of the deformed axis curvature. The use of integrated results of inclinometric and geodetic measurements allows for the correct calculation of the shape of the axis of the deformed retaining structure, the displacement of the wall crown and the displacements of the wall below the bottom of the excavation. The additional use of terrestrial laser scanning enables wider range monitoring of deformations and displacements of the retaining structure and adjacent buildings as well as searching for leaks in the diaphragm wall.

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