VERSITA
Studia Geotechnica et Mechanica, Vol. XXXV, No. 3, 2013
DOI: 10.2478/sgem-2013-0028

DISPLACEMENT MONITORING AND SENSITIVITY ANALYSIS IN THE OBSERVATIONAL METHOD

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Abstract: This work discusses the fundamentals of designing deep excavation support by means of observational method. The effective tools for optimum designing with the use of the observational method are both inclinometric and geodetic monitoring, which provide data for the systematically updated calibration of the numerical computational model. The analysis included methods for selecting data for the design (by choosing the basic random variables), as well as methods for an on-going verification of the results of numeric calculations (e.g., MES) by way of measuring the structure displacement using geodetic and inclinometric techniques. The presented example shows the sensitivity analysis of the calculation model for a cantilever wall in non-cohesive soil; that analysis makes it possible to select the data to be later subject to calibration. The paper presents the results of measurements of a sheet pile wall displacement, carried out by means of inclinometric method and, simultaneously, two geodetic methods, successively with the deepening of the excavation. This work includes also critical comments regarding the usefulness of the obtained data, as well as practical aspects of taking measurement in the conditions of on-going construction works.

1. INTRODUCTION – THE SCOPE OF THE WORK

A wide range of problems associated with geotechnical designing in conditions of a significant variability of data entered into calculations may be solved with the use of methods developed by Peck [8]. However, such an approach may be used only if it is possible to revise the design solutions on the basis of the observed behavior of the structure. When the observed mechanism of failure may potentially occur at the time which makes it impossible to introduce any changes, it is necessary to assess the risk of failure. Although the techniques for objective estimation of reliability of a structure have long been available, and the benefits of their application are known, they are very rarely put into practice [12], [13]. This results especially from the mode of data preparation which differs from the traditional one (description of the main random variables chance) and scarce verification options, which puts off the designers who are successful in using traditional methods.

2. OBSERVATIONAL METHODS – THE QUALITY OF THE DESIGN AT THE COST OF UNCERTAIN COST ESTIMATE

Observational methods are widespread in the design and execution of deep excavations in many countries [1], [8]. Particular attention is paid to the parameters of a model, and the models used are primarily the ones which are easy to analyze and well-proven in practice – even though they do not always exhibit the maximum fidelity in modeling the behavior of both the structure and the soil.

The characteristic attribute of those methods is the dynamic data correction (inverse analysis), performed on the basis of observations and measurements at given stages of construction. Observational methods will be gaining practical significance, because contemporary trends in standardization indicate that the conditions of use should be verified as thoroughly as demanded by the obligatory ultimate capacity check. The idea of observational method is based on the measurement and analysis of a series of horizontal and vertical dislocations. The measurements include:

- movements of the wall's top edge (starting from the "zero" level right after inserting it in the soil),
- displacement of the wall while unearthing at the level of the anchorage (if there is one),
- displacement of the wall base (by means of inclinometric method).

The displacement of the wall base is determined in principle indirectly, on the basis of inclinometric and geodetic measurements. If the displacements of the point on the top of the wall are identical, it means that the displacement of the base is nil. If not, this indicates that the wall base is not submerged in the soil deep enough – and the wall "flees". The inclinometric measurement will make it possible to designate the deflection of the wall (the values of displacement at the points which remain inaccessible to geodetic measurement). Determining those displacement values is usually crucial for the estimation of the interior forces in the excavation support, anchorage or thrusts, as well as for assessing the impact on structures and underground infrastructure network located in the zone of the excavation direct impact [7]. In addition, displacement values allow us to designate other values for buildings and other structures located within the excavation impact zone:

- average settlement,
- differences in horizontal settlement and the ensuing tilt,
- average horizontal displacement and the difference in the displacement values.

The results of monitoring and measurements enable systematic verification of the design assumptions – regardless of the method which was used in calculations. The observational method is, therefore, very valuable in supporting the implementation of major projects where, regardless of the designing method, it provides the data which confirm (or reject) the correctness of the assumptions expressed in the design. At the same time, the use of the observational method introduces certain difficulties in the

preparation of the project timetable regarding materials and costs. The updating of the design assumptions may create a number of conflicts on the line designer–contractor–investor (payer). Although the schedule of the tests (monitoring) causes certain organizational complications and charges the investor, it brings the benefits of avoiding the risk of failure, downtime and financial claims, which cannot be overestimated.

The Institute of Geotechnics of Wrocław University of Technology collects the data from the projects which included monitoring. For example, work [10] presents the results of calculations carried out by means of the MES program, but the authors performed the analysis of deformation on the basis of the design data and then on the basis of the data obtained from the inverse analysis. Differences were not significant, which confirmed the accuracy of the original assumptions. The measurements, however, made it possible to assess a number of factors difficult in modeling, such as technology of constructing the sheet pile wall, or supporting the adjacent structures (jet-grouting).

Work [5] also employs the inverse analysis using MES to define the parameters of the fill soil which exerts pressure on the sheet pile wall. Inclinometric measurements of the wall displacement – and of the soil behind the wall – were the basis for the calibration of the model.

3. OBTAINING PARAMETERS FOR DESIGNING ON THE BASIS OF THE INVERSE ANALYSIS

A designer who wants to use observational method in designing needs to resolve the following issues:

- The selection of basic data (random variables) on the basis of the analysis of the model sensitivity.
- The choice of the measurement points and displacement to be measured in the monitoring process in order to calibrate the basic data (random variables) and to determine their calculation parameters in accordance with the required level of safety.

Paradoxically, these issues are solved, in most cases, on the basis of intuition and experience, and less frequently by detailed random analysis.

3.1. THE SELECTION OF VARIABLES IN SAFETY ANALYSIS

Intuition suggests that the safety of a retaining wall depends of the following parameters:

- the soil strength parameters (angle of friction and cohesiveness in the Coulomb–Mohr model – for non-cohesive soil types one may choose the coefficient of pressure),
- soil weight and ground water level (hydrostatic pressure),

- realistically developed static diagram (load of the surcharge, level of the excavation bottom at successive stages of unearthing the wall, the level of anchoring).

The methods of safety analysis which derive from the theory of reliability require specialized software and skills in designating the function describing the surface of the limit state (e.g., by means of the "response surface" method). When it is impossible to easily define such a function, and, at the same time, when the data for the design (basic random variables) are independent (which is mostly true in the case of designing a retaining structure), then the sensitivity analysis may be carried out using the authors' original method based on Duncan's proposal [3], which proceeds as follows:

- determine the searched value – safety factor F for the average values $\overline{X}_k$ of all random data entered into calculations,
- determine the searched value (e.g., F) by substituting subsequent values of $\overline{X} \pm \sigma_x$ (in total, $2 \times N$ calculations, if the number of variables equals N). $\overline{X}$ is the average value of the random variable, and σ_X is the standard deviation,
- determine the alteration of the searched value, depending on the alterations of individual parameters, e.g.,

$$\Delta F_k = F(\overline{X}_k + \sigma_{Xk}, \overline{X}_i) - F(\overline{X}_k - \sigma_{Xk}, \overline{X}_i), \tag{1}$$

- calculate the deviation of the searched value by means of the formula

$$\sigma_F = \sqrt{\sum \left(\frac{\Delta F_k}{2} \right)^2} \tag{2}$$

- and the coefficient of variation

$$V_F = \frac{\sigma_F}{F(\overline{X})}, \tag{3}$$

- the estimation of the average value of the searched value and the estimation of its deviation make it possible to estimate the reliability factor β on the basis of the following formula

$$\beta(F) = \frac{\ln\left(\frac{F(\overline{X})}{\sqrt{1 - V^2}} \right)}{\sqrt{\ln(1 + V^2)}}. \tag{4}$$

The obtained values of reliability factor β obviously depend on the assumed hypothesis about the type of distribution of F (here, the traditional lognormal distribution was assumed), but they allow us to estimate safety in a way which is more objective than merely on the basis of the F value (or SM – safety margin). One may notice that the calculations performed make it possible, in addition, to calculate – in a simplified

way – the parameter which defines the sensitivity of the safety factor value (or the margin of safety) to the variability of the *k*-th basic variable

$$\alpha_{Fk} = \frac{\Delta F_k}{2 \cdot \sigma_F}. \tag{5}$$

The sensitivity factors suggested by formula (5) show the property of $\sum \alpha_{Fk}^2 = 1$ and in simple geotechnical situations they may be proved not to depend in a significant way on the manner they were determined (for *F* or SM). The data for calculations which have the highest sensitivity factors α have the most considerable influence on the safety of a structure within a given parameter, and as such, they should be thoroughly calibrated at each subsequent stage of analysis in the observational method. In order to illustrate the simplicity of calculations with the use of the above-suggested method, the stability of a sheet pile wall in non-cohesive soil was analyzed in the following situations:

- for a wall with the penetration depth *D* below the bottom of the excavation, the variable height *H* of the leap is assumed (which may be understood as a random loading of the surcharge),
- for a wall with a permanent length $L = D + H$, one analyses the influence of a potential deepening of the excavation (random depth *H* of the excavation),
- in addition, in both situations the randomness of the coefficient of earth pressure K_a (the randomness of the angle of external friction).

The selection of the cantilever element was conditioned by the fact that it is present in the case of virtually every excavation (as a transitional phase) and is responsible for significant horizontal displacement of the sheet pile wall [7]. At the same time, another motivation behind that choice was to reduce the number of random variables. That element leaves out the issues related to the initial compression and the creeping of anchorage, as well as to the availability of actual data from the field tests [9].

The height of the wall under analysis: $L = 8.0$ m. The depth of the excavation: $H = 4.0$ m. The soil characteristics are those of medium sands, medium compact, with a low dampness: $\gamma = 18.0$ kN/m^3, $\Phi = 30°$.

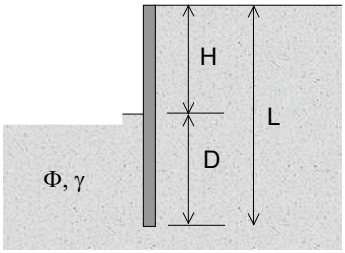

Fig. 1. The diagram assumed for analysis

The calculations were carried out with the assumption of classical theory of pressure and the assessment of safety as proposed by Duncan [3], which required only the

use of a spreadsheet, making it possible to perform repeatable static calculations. Assuming that the distribution of the safety factor was lognormal, we obtained similar values of the reliability factor. The safety factor, for the wall penetration beneath the excavation bottom D and the maximum bending moment M, is defined as follows:

- $F_D = D_0/D$, where D_0 and D are the design depth and the calculated depth, respectively,
- $F_m = M_0/M$, where M_0 is the bending strength, and M is obtained from calculations.

For the penetration depth D: $\beta_D = 2.41$, $\alpha_H = 0.62$, $\alpha_{Ka} = 0.79$.
For strength M: $\beta_M = 2.34$, $\alpha_H = 0.84$, $\alpha_{Ka} = 0.55$.

If we assume that the measure of safety is not the safety factor F, but the safety margin SM in the shape of the difference:

- $SM_D = D_0 - D$, where D_0 and D are the subsequent depths as above,
- $SM_M = M_0 - M$, where M_0 and M are the strengths as above,

then we obtain the following results:

For penetration depth D: $\beta_D = 3.06$, $\alpha_H = 0.61$, $\alpha_{Ka} = 0.79$.
For strength M: $\beta_M = 4.05$, $\alpha_H = 0.83$, $\alpha_{Ka} = 0.56$.

The obtained results confirm that when we change the criterion from the safety factor to the safety margin, there is a risk that the assessment of safety expressed by means of coefficient β will also alter. It is, however, important from the point of view of calibrating the model using the field test results (monitoring the structure's displacement) that there is no significant alteration in the assessment of importance of particular data (that assessment is expressed with the sensitivity factor α).

It must be observed that the most frequent situation in designing is the assumption of a constant wall length: $L = D + H$. In such a case, when the height of the ground leap increases, the depth of penetration D automatically drops. In such a situation – possible both at the construction site and, at the same time, potentially more dangerous than the one described above, in accordance with Duncan's proposal we obtain for the penetration depth D

$$\beta_D = 1.88, \quad \alpha_H = 0.78, \quad \alpha_{Ka} = 0.62.$$

The control calculations by means of the Hasofer–Lind method were performed using the COMREL specialized software, which gave the following results

$$\beta_D = 2.02, \quad \alpha_H = 0.78, \quad \alpha_{Ka} = 0.63.$$

In a situation in which the unplanned excavation causes the decrease in the wall's penetration depth below the excavation bottom, one may observe together with the drop of the reliability factor β a significant shift in the weights α_i introduced to the calculations of basic variables. It is noteworthy that while the safety measures, even though the applied methods enable their maximum objectivization, show certain variability, the sensitivity factors α are unusually stable, independent of the manner in

which the analysis is carried out. This makes it possible to state that the suggested procedure of estimating a structure's safety proved to be, in a way as a side effect, a very efficient tool in assessing what is significant and should, therefore, be included in the calibration process in designing by means of the observational method.

3.2. METHODS OF OBTAINING DATA WHICH FORM THE BASIS OF THE MODEL CALIBRATION

The estimation of mechanical interactions affecting a retaining structure is possible by the direct measurement of the pressure exerted on the wall, which requires a specialized machinery that may easily be destroyed in the process of driving the wall into the ground. It is much easier to take indirect measurement – by measuring the displacement of the visible part of the wall or (even better: "and") the inclinometric measurement in steel pipes earlier attached to the sheet piles.

3.2.1. INCLINOMETRIC MEASUREMENT (RELATIVE DISPLACEMENT)

Inclinometric measurement makes it possible to determine the relative horizontal displacement at the testing stations prepared especially for that purpose. Such a station is made by welding a steel profile (with a square cross-section) into a sheet pile. The profile's length should be similar to the length of the sheet pile, and it is sufficient to have the knit line on a selected section of the sheet pile. The profile is closed (by welding) at the bottom and then driven into the ground together with the sheet pile. Another way of constructing the testing station is to install the inclinometric pipes in the boreholes and filling the remaining space around them with cement. That way of building a testing station requires an additional analysis of the value of the structure displacement in comparison with the displacement of the soil at the place of measurement. An additional important issue is the composition of the cement slurry surrounding the inclinometric pipe. Its strength should be similar to the strength of the soil so that the obtained values of displacement are reliable.

The inclinometric measurement consists in introducing a special sounder into the inclinometric pipes (profiles) at each of the testing stations. The measurement determines the deflection of the inclinometric sounder between the subsequent measurement levels separated from one another by the same and equal distance. On the basis of the difference of the measured angles – between the periodic measurement and the initial ("zero") measurement – one calculates the value of the increment of the relative displacement.

Only the sum of all the increments of displacement, starting with the lowest level on the testing station up to the searched measurement level, makes it possible to determine the value of the relative displacement at a given level. The subject of inclinometric measurements was described in detail in article [5] and book [4]. The advantage of the inclinometric measurement is the possibility of obtaining information about the displacement of the retaining structure surrounding the excavation, also be-

low its current bottom. That is not possible for typical geodetic measurements, where the measurement is taken for the visible part of the sheet pile wall, starting with the top edge before unearthing and extending the scope of the measurement successively as the excavation deepens. A weak point of the inclinometric measurements is their relative nature. The recorded shapes of the inclinometric pipe from different measurement periods are compared, with the assumption that the lowest measured level does not change its location. Typically, that assumption is wrong, which may lead to an erroneous determination of the value of displacement of the retaining structure. Geodetic monitoring of displacement should be an indispensable supplement of inclinometric measurements.

3.2.2. GEODETIC MONITORING OF (ABSOLUTE) DISPLACEMENT

Geodetic measurement of horizontal displacement makes it possible to determine the absolute values in the external (fixed) reference frame. The type of the applied methods and measuring tools must be precisely adjusted to the specific characteristics of the structure under survey and its surroundings, to the dynamics and the values of the expected displacement, as well as the required level of accuracy and speed of their determination. The most popular methods are described below, to begin with the oldest one.

Alignment method, also known as constant straight line method – is the most frequent way of surveying the displacement of elongated objects. By means of that method it is possible to determine horizontal displacement in the direction perpendicular to a vertical reference plane. The reference frame is established by four points joined with a straight line, two at each side of the structure under survey, outside the zone of deformation (Fig. 2). Whenever possible, the location of the points is selected in such a way so that the check points are situated along the reference plane, at a short distance (up to several centimeters) and at a similar height. The instrument is placed at point P2, via forced centering, and the target – at point P3. The surveying is carried out by means of special stable theodolites with telescopes with large magnification,

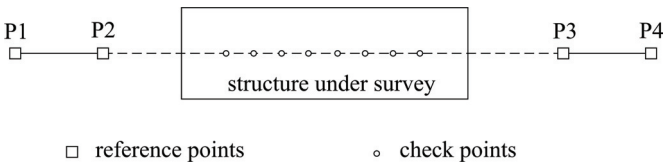

Fig. 2. Alignment method scheme

called alignment telescopes, or high-precision electronic tacheometers. The measurements are taken in two positions of the telescope, sometimes in several measurement series. Mutual fixity of the points of reference is controlled by analyzing their horizontal displacement and by checking the horizontal angles in relation to the established additional reference points, e.g., P1 and P4.

Depending on the method of horizontal displacement measurement at the control points, there are some varieties of the aforementioned method [2]:

- Geometric-alignment method, in which the vertical reference plane is determined by the target axis of a theodolite or an alignment telescope placed at point P2 and oriented towards point P3. At each of the control points a special target is positioned, which is shifted by means of a micrometric screw to fit into the target line. The values of horizontal displacement in the crosswise direction to the reference line are calculated by means of a comparison of the readouts from the micrometric screw that come from different survey periods. Sometimes immobile targets are used and the value of the transverse displacement is read out from an alignment telescope with an optical micrometer.
- Trigonometric-alignment method, in which a high-precision tacheometer is sighted on an immobile target (situated at the check point) and the parallactic angle is measured.
- Electromechanical alignment method, in which the reference line is established in the form of a metal string stretched between points P2 and P3. At check points, a special device is fixed, equipped with a container filled with liquid. In the container there is a float attached to the metal string. The displacement of the control point results in the change of the position of the float in the container, which is recorded by electric sensors and may be transmitted telemetrically to the surveying station.
- Laser-alignment method, in which a laser beam stands for the reference line. The target placed at the control point may be manually introduced into the laser beam by means of a micrometric screw and then the displacement value is read out of the micrometer. Another option is an immobile target equipped with a photodetector, which records the position of the laser spot in relation to the centre of the target.

Trigonometric method – consists in taking multiple measurements of horizontal and vertical angles and distances, at specific time intervals, aiming at the check points from the fixed reference points located outside the zone of impact of the structure under survey. The surveying is carried out with the help of theodolites or tacheometers with high accuracy of angle and distance measurement. For each of the periodic surveys, fixed reference points are identified. The coordinates of the check points are calculated by means of the least squares method, based on a set of observational data in the form of angular-linear network or multiple intersections: angular, angular-linear or linear ones. The differences of the coordinates of the points under investigation, calculated from the particular measurement cycles, make it possible to calculate the absolute displacement of those points. The trigonometric method allows determining the displacement of the support of a deep excavation on many levels, both alongside the sheet pile wall, as well as perpendicular to it (towards the excavation). It must be, however, remembered that there is a time shift in the initial measurement for the subsequent lower levels in comparison

with the highest level of the control points. That results from the progress in excavation works and uncovering the subsequent parts of the sheet pile wall.

Structural monitoring is a modern system combining different techniques of determining the displacements: absolute measurements of displacement (using geodetic methods) with the relative measurement of displacement, as well as with various types of sensors recording the behavior of the structure under scrutiny. Structural monitoring makes it possible to record automatically the condition of the structure, cyclically at predefined time intervals, for example, every 10 minutes. Thus collected data are gathered, corrected in relation to the influence of the survey environment and calculated in the appropriate manner. The obtained values of displacement are compared with the permissible values, visualized and sent remotely to relevant supervisory bodies. The system ensures a round-the-clock control of the structure under scrutiny in the real time, together with the possibility of automatic alarm signaling. The main component of the system is the motorized electronic tacheometers, which offer the measurement of the angles with the mean error that does not exceed ±1″.

For standard distances smaller than 1000 m, the mean error of the distance measurement ranges from ±0.5 mm to ±2 mm. The tacheometers have the function of the automatic target detection; the target is indicated by means of a geodetic reflector [6] and located at the distance of no more than 3000 m. The second component of the structural monitoring system is the GNSS receivers operating in different modes: the static or the real-time kinematic (RTK) mode. The static GNSS measurements are carried out at the reference points, and the kinematic measurements allows recording the displacement of check points at one-second intervals. A typical solution is to combine the antennas of the GNSS receivers with reflectors or tacheometer stations, and thus creating the integrated control networks [11].

Terrestrial Laser Scanning, used in the survey of displacement and deformation, has recently become an increasingly frequent and rapidly evolving technology which makes it possible to survey a great number of points per second (e.g., laser scanner Leica ScanStation P20). A vertically rotating prism sends the impulses of a laser beam which is reflected from the structure under scrutiny. Simultaneously the scanner rotates horizontally with given increments. For each point under survey the reflectorless measurement of the distance (up to about 250 m) is taken, and the horizontal and vertical angles are recorded. The accuracy of the distance measurement of a section of no more than 50 m amounts to 3 mm. The density (the number) of the points under survey is defined by way of determining the horizontal and vertical size of the mesh of rectangles which the points under survey constitute on the predefined surface. The minimum distance between the points may be smaller than 1 mm. The scanner is equipped with a high-resolution digital camera with an automatic zoom, which takes the photos of the structures under survey and thus enables the archiving of their condition and their realistic visualization. In the case of large structures, the separate scanner stations are connected with one another by way of scanning the linking points (tie points) indicated by special targets. The linking points are the

reference points, if the range enables that. In the case of the deep excavations with the reference points situated at a considerable distance, a control network may be set up. The main components of that network, surveyed by means of standard geodetic methods, are: the planned scanner station, the linking points and the reference points. Even though the precision of the terrestrial laser scanning is relatively lower in determining the position of a single point, the laser scanning has one considerable advantage. In a short time we obtain millions of check points which give a completely metric, three-dimensional model of a deep excavation, the excavation support and the structures located in the direct neighborhood. That model is extended with photographic documentation. That is a remote method in which no direct contact with the structure is necessary. The method makes it possible to record the condition of the whole structure, and not only of some selected points. Laser scanning may also be integrated with the GNSS satellite receiver.

4. FIELD TESTS PERFORMED

The tests presented below were carried out on the construction site of a large public building, located near high-density city housing. The construction requires a 4-meter deep excavation, without the need for lowering the water table. Similarly as in the case

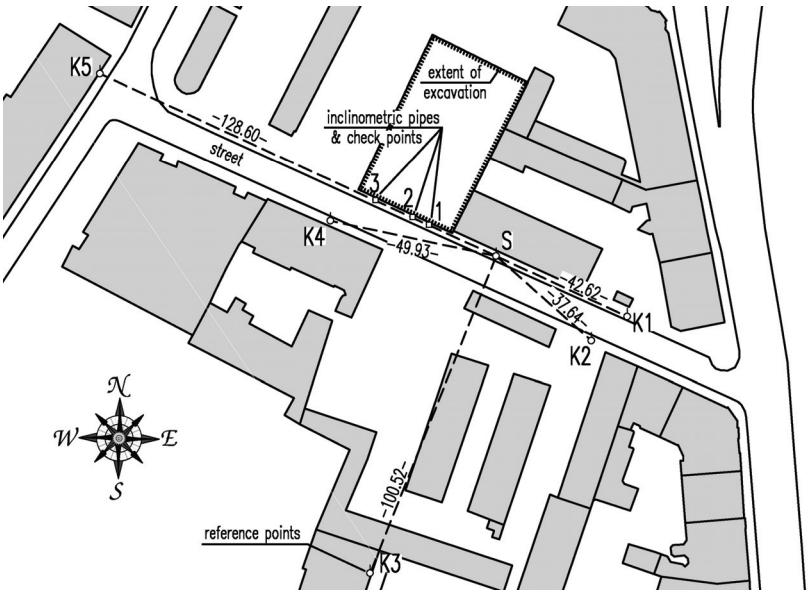

Fig. 3. The arrangement of check points and reference points

study presented before, which showed the rules for data selection (basic random variables), the soil features correspond with those of fine and medium sands, medium

compact, medium damp: $\gamma = 18$ kN/m^3, $\Phi = 30°$. Due to the necessity of restraining the displacement of the sheet pile wall towards the center of the excavation, steel sheet piles, with the length of 10 m each, were used. Figure 3 presents the location of the sheet pile wall and the testing stations.

4.1. INCLINOMETRIC MEASUREMENTS

The testing stations consisted of three square profiles with the dimensions of 50×50×2 mm, closed from the bottom, and welded to the sheet piles before they were driven in the ground. At each testing station, the inclinometric measurement was performed in four perpendicular directions (which was possible owing to the shape of the pipes' cross-section), always starting from the same direction. Fixed levels of measurement were assumed, at a distance of 0.5 m from one another. The initial measurement was taken before the beginning of the unearthing of the retaining structure on 13 June 2011. Each subsequent measurement reflects the progress of the works on the site: the first control measurement took place on 24 June 2011 (excavation at the level of –2.5 m), the second measurement – on 18 July (excavation at the level of –4.0 m).

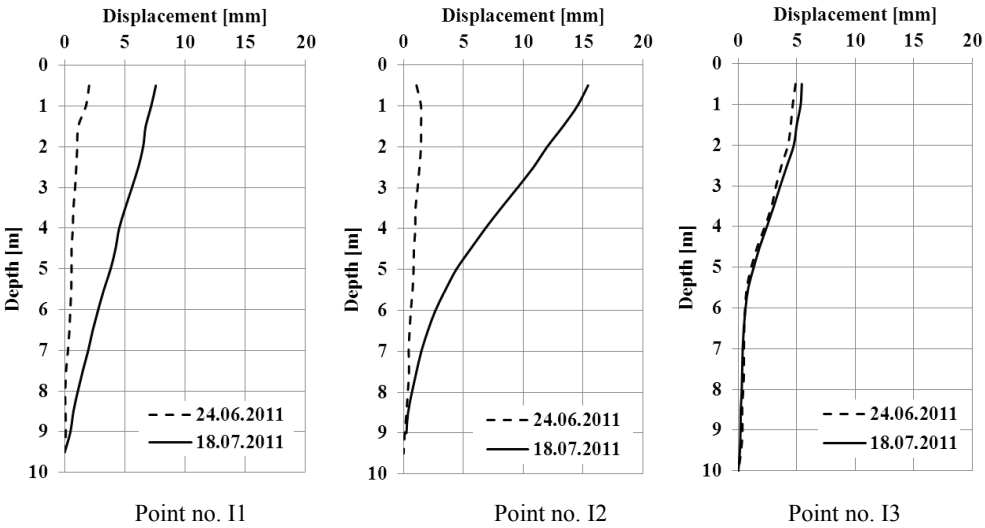

Fig. 4. Displacement of control points I1, I2 and I3 towards the excavation

Figure 4 shows the recorded values of relative displacement. Point I2, situated in the middle of the sheet pile wall, is subject to the largest final displacement. It is the place with the maximum load exerted on the structure and where the wall exhibits the plane state of strain (without the effects typical of the corners of the excavation, which radically reduce displacement). Point at the very top of the sheet pile wall is subject to

the largest displacement, and its value equals 15.4 mm. Such a result was expected due to the cantilever-like role of the wall. In Fig. 4 one may observe the inflection of the graph below the excavation bottom. That measurement result is particularly valuable, as it shows the displacement in a place hardly accessible for geodetic measurements and, at the same time, it makes it possible to estimate the scale of displacement necessary for the appropriate assessment of the passive earth pressure which would stabilize the cantilever wall. At point I1, located at the smallest distance from the existing building, the initial displacement is similar to I2, whereas the final displacement is considerably smaller, as the exerted load is smaller due to the corner spanning.

The final point I3 was located closest to both the entrance gate to the site and the service road on ramp. For this reason, the end of the retaining structure situated in that area was not entirely unearthed. This is visible on the diagrams of the displacement. The last measurement points to a minor increment of displacement between the one measured at the level of unearthing above the half of the excavation depth and the one observed at the full excavation depth. It may be observed that the obtained displacement values at different levels of the wall are very valuable data for the purpose of calibration of the wall's behavior model (e.g., numeric one), and allow us to estimate precisely, by means of the inverse analysis, such basic data for designing as: surcharge load, the height of the unearthed wall and the coefficient of earth pressure (the angle of internal friction).

The only flaw of the inclinometric tests performed was the risk that the values measured against the wall's base at the depth of about 10 m are not "independent", but influenced by the displacement of the wall base towards the excavation center, which is indispensable in order to mobilize the passive earth pressure below the excavation bottom. That is why the systematic geodetic survey of the wall top edge was carried out, which made it possible to determine the objective (absolute) displacement values.

4.2. GEODETIC SURVEY OF DISPLACEMENTS

In order to perform a geodetic survey of the excavation support, a control network was set up (Fig. 3). The network consisted of the instrument station S, five reference points (from K1 to K5), and check points located at the inclinometric testing stations. The markings for the points subject to geodetic survey include the same numbers as for the inclinometric stations, and the letter "I" was abandoned. The measurement of horizontal displacement was taken by means of two independent methods: alignment and trigonometric method, on the following dates: initial measurement – 13 June 2011, the first control measurement – 1 July 2011, the second control measurement – 19 July 2011, and the third control measurement – 22 July 2011. The device used in the survey was the electronic tacheometer SOKKIA SET3030R3, with the telescope's magnifying power ×30, the angle measurement accuracy of ±3", and the precision of distance measurement while using the reflector mode of ± (2 mm + 2 ppm).

In the alignment method, the straight line of reference was marked by points S and K5. The readouts were made with the use of a special ruler placed next to each of the inclinometric pipes under scrutiny. The survey was performed in two positions of telescope, in two measurement series, and its results are presented in Fig. 7.

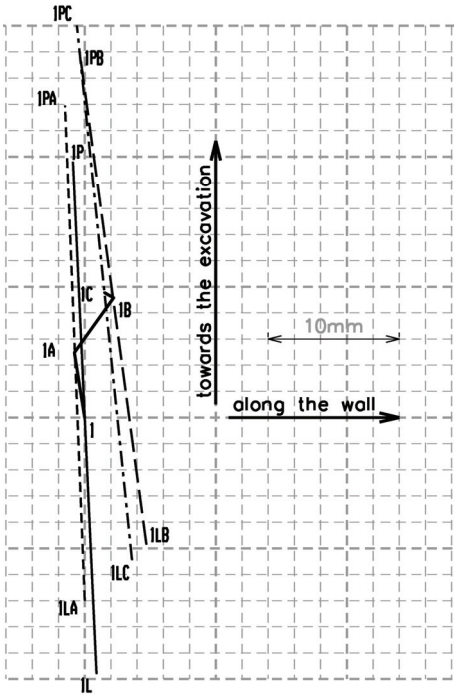

Fig. 5a. Point no. 1 (at the adjacent, already existing structure) – a minor longitudinal displacement (slightly above the measuring error), a minor torsion tendency

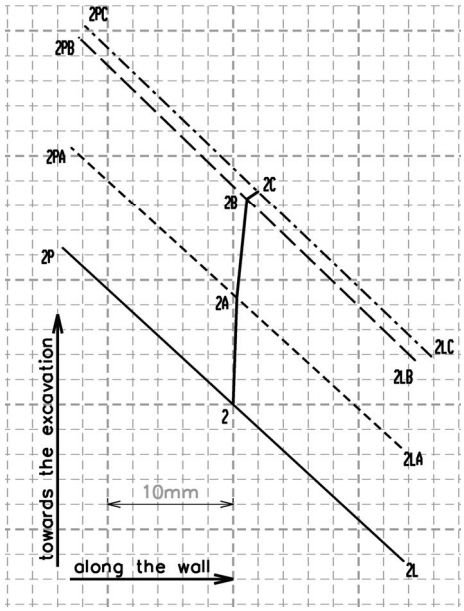

Fig. 5b. Point no. 2 (near the excavation center) – longitudinal displacement within the limits of measuring accuracy

In the case of the trigonometric method, horizontal angles were measured by means of a directional method in three series with the simultaneous measurement of distance. The measurements were made from station S to all five reference points, but for point K3 (located on the roof top) only the directions were measured (without measuring the distance). For each inclinometric pipe two control points were surveyed, located at the top edge of the pipe and marking its selected diagonal. The end of the diagonal situated nearer to the excavation was given the symbol "P", and the end of the diagonal facing the street was marked with "L". The symmetry axis of the pipe (calculated at the middle of the profile's diagonal) was marked with the same number. The changes in the position of the symmetry axis of the inclinometric pipe show the displacement under study. The initial measurement has no additional mark-

ings. The subsequent measurements were given additional letters: “A”, “B”, “C”. The axes of the reference frame were assumed such that one of them ran along the sheet pile wall, and the other one – perpendicular to the wall. The adjustment in directional method made it possible to estimate the standard error of the direction measured in three series, which equaled: for the initial measurement 0.56 mgon, and for the subsequent control measurements 0.59 mgon, 1.57 mgon, and 0.83 mgon, respectively.

A slightly worse accuracy of the second control measurement was caused by the unfavorable conditions. The third control measurement was performed just for proof. The obtained results are shown in Figs. 5a–c.

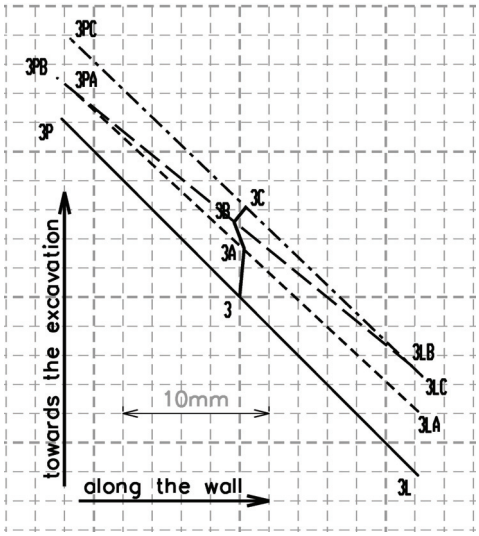

Fig. 5c. Point no. 3 (at the entrance gate to the site) – longitudinal displacement, irrelevant from the point of view of their determination accuracy

Station S, common for both methods, could be placed on the border of the potential range of impact of the excavation. That is why before the results from each control measurements were further elaborated, the stability of the position of point S was checked. This was made each time by adjusting the resection and calculating the coordinates of station S in relation to five reference points (located outside the excavation impact zone). The alterations of the station’s coordinates between the initial measurement and the subsequent control measurements did not exceed 2 mm, which remained within the limits of the double value of a mean error of their determination. On that basis the stability of point S was confirmed.

4.3. THE COMPARISON OF INCLINOMETRIC AND GEODETIC METHODS

When analyzing the data from the diagrams in Figs. 6 and 7, it must be observed that the displacements of the wall’s top edge measured by means of geodetic methods are each time slightly larger than the displacements measured by means of the

inclinometric method. This is associated with the fact that the inclinometric measurement is relative – it is taken in relation to the lowest measurement point which is not fixed, because its displacement is indispensable due to the passive earth pressure mobilized beneath the bottom of the excavation.

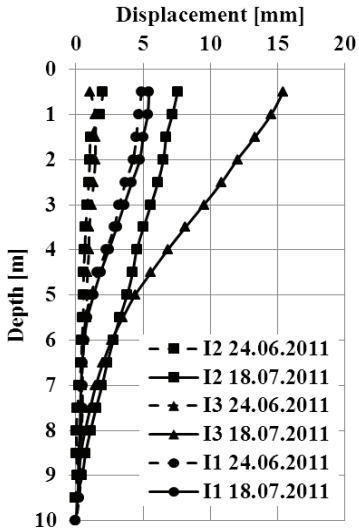

Fig. 6. Subsequent inclinometric displacement on the wall

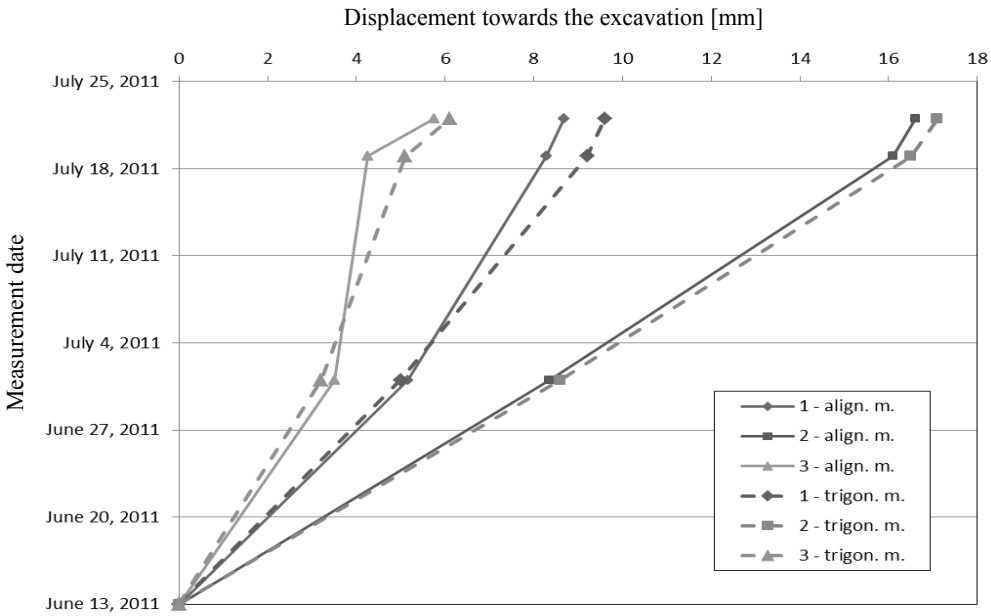

Fig. 7. The increment of displacement values of the wall's top edge measured by means of geodetic techniques

5. SUMMARY – PRACTICAL ASPECTS OF DESIGNING BY MEANS OF THE OBSERVATIONAL METHOD

The research carried out aimed at checking the usefulness of the inclinomeric and geodetic methods of controlling horizontal displacement, with respect to obtaining input data for designing a deep excavation support by means of the observational method. The measurements of displacement make it possible, in further analysis, to calibrate the computational model of a cantilever wall and, as a result, to assess the stability and to determine the internal forces interacting within the support structure. The earlier sensitivity analysis allows us to select and calibrate the data (basic random variables in the analysis of reliability), on which it actually depends if the complex safety criteria can be met. The gathered experience enables us to give a critical feedback to the methodology of the measurements performed. What seems to play the decisive role in the case of the inclinometric measurements is the proper preparation, arrangement and fitting of the inclinometric pipes.

- When the subject of analysis is the displacement of the sheet pile wall, then the pipe with the length corresponding to that of the wall's should be fixed rigidly to the external part of the wall (on the side of the soil, not the excavation). That will protect the pipe from damage during the deepening of the excavation. The pipe should – at the same time – reach above the ground, which will increase the safety of using the inclinometer.
- The recommended pipes are the ones with the square cross-section, whose diagonal will be perpendicular to the sheet pile wall's axis. That makes it possible to assess quickly the displacement – while the tests are performed.

The accuracy of geodetic measurements largely depends on the chosen method of measurement and depends on the location of the testing station.

- The survey should be carried out from the station situated on the axis of the wall, which makes it possible to employ the alignment method. Unfortunately this method usually limits the possibilities for geodetic control only to the check points located on the top edge of the wall.
- Trigonometric method of measuring the horizontal displacements gives the opportunity for more flexible scheduling of tacheometer's station. There is also the possibility to take measurements from the station located outside the excavation, where line of sight is perpendicular to the wall. It enables the network of the check points to be expanded with the new points unearthed at the subsequent stages of the deepening of the excavation. One must, however, remember that the subsequent points (apart from those located on the wall's top edge) do not have the "zero readouts" of the initial measurement, so their usefulness in calibration is reduced to determining displacement at later stages.
- In both methods, reference points should be located away from the zone of impact of the excavation and earth works. It is necessary to find a compromise

between potential stability of the tacheometer's station and the measurement accuracy (which decreases with the increase of the distance from the station to the check points). In developing measurement results from each epoch it is necessary to verify stability of the reference points.

Designing by means of the observational method will gain popularity with the growing use of the "design and build" system, in which the contractor is responsible also for the overall concept and designing. The advances in software which enable the flexible response of the designer to the data obtained from the construction site are also a favorable circumstance which supports this technically optimal, but financially difficult, manner of project execution.

That is why the research in this area is valuable, as it allows us to gain experience and further to elaborate guidelines for designing by means of the observational method – from the point of view of both selecting data for the inverse analysis, as well as obtaining the information about a structure displacement in order to calibrate those preselected data.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to AARSLEFF Sp. z o.o. for making available the access to the building site and the measurements of the sheet pile wall displacement.

REFERENCES

[1] BROŚ B., *Metoda obserwacyjna w rozwiązywaniu zagadnień geotechnicznych*, VII Krajowa Konferencja Mechaniki Gruntów i Fundamentowania, Wydawnictwo Politechniki Poznańskiej, 1984.

[2] BRYŚ H., *Geodezyjne pomiary odkształceń i przemieszczeń zapor wodnych*, Wydawnictwo Politechniki Krakowskiej, Kraków, 1996.

[3] DUNCAN J.M., *Factors of safety and reliability in geotechnical engineering*, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 2002, Vol. 126, No. 7.

[4] DUNNICLIFF J., *Geotechnical instrumentation for monitoring field performance*, Wiley, New York, 2004.

[5] GÓRSKA K., WYJADŁOWSKI M., *Analysis of displacement of excavation based on inclinometer measurements*, Studia Geotechnica et Mechanica, 2012, Vol. XXXIV, No. 4.

[6] KARSZNIA K., *Geodezyjny i geotechniczny monitoring obiektów inżynierskich w ujęciu dynamicznym. Wykrywanie słabych punktów*. Nowoczesne Budownictwo Inżynieryjne, 2008, No. 4.

[7] LONG M., *Database for retaining wall and ground movements due to deep excavations*, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 2001, Vol. 127, No. 3.

[8] PECK R.B., *Advantages and limitations of the observational method in applied soil mechanics*, 9th Rankine Lecture, Geotechnique, 1969, No. 2.

[9] PORSVIG M., THORSEN T., *Reliability index for an anchored sheet pile wall*, International Symposium. Limit state design in geotechnical engineering. Danish Geotechnical Society, Vol. 2, Copenhagen, 1993.

[10] RYBAK J., ZAREMBA S., *Zastosowania pomiarów geodezyjnych w geotechnice*, Geodezja w budownictwie, Materiały jubileuszowej sesji naukowej, Gdańsk, 18.06.1999.
[11] van CRANENBROECK J., BROWN N., *Networking Motorized Total Stations and GPS Receivers for Deformation Measurements*, FIG Working Week, May 22–27, Athens, Greece, 2004.
[12] WHITMAN R.V., *Evaluating calculated risk in geotechnical engineering*, ASCE Journal of Geotechnical Engineering, 1984, Vol. 110, No. 2.
[13] WHITMAN R.V., *Organizing and evaluating uncertainty in geotechnical engineering*, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 2000, Vol. 126, No. 7.