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Research the Integration of Geodetic and Geotechnical Methods in Monitoring the Horizontal Displacement of Diaphragm Walls

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Abstract. This article investigates the integration of geodetic and geotechnical methods for monitoring the horizontal displacement of diaphragm walls. The results show that when the horizontal displacement is measured by the geotechnical method using an inclinometer sensor, the center point at the bottom of the guide pipe is usually chosen to be the origin to calculate displacements of the upper points. However, it is challenging to survey the bottom point for checking its stability directly. If this bottom point moves, the observation results will be incorrect. Thus, the guide pipe must be installed in the stable rock layer. But in the soft ground, this rock layer locates more deeply than the diaphragm walls, so the guide pipe cannot be laid out at the required location. Geodetic methods can directly observe the displacement of the center point on the top of the guide pipe with absolute displacement values at high accuracy. Because the displacements of observation points are determined at stable benchmarks, these values are considered the pipe's displacement. Thus, an integrated solution allows the center point on the top of the pipe to be the origin to calculate the displacements of different points located inside the diaphragm wall. Then, the calculated values are calibrated back to the inclinometer observed values to achieve highly reliable displacement, which reflects the moving of diaphragm walls. An experiment integrating the geodetic and geotechnical methods is conducted with an observation point at a depth of 20 meters at a construction site in Ho Chi Minh city. The deviations of the top point that are observed by the two methods are -4.37 millimeters and -3.69 millimeters on the X-axis and the Y-axis, respectively. The corrected observed results prove that the integrated solution has a good efficiency in monitoring the horizontal displacement of diaphragm walls. The bottom point observed by an inclinometer is unconfident enough to choose to be a reference point.

Keywords: Deformation monitoring, Diaphragm wall, Engineering surveying, Soft ground

1. Introduction

In Vietnam, big cities are usually located in delta regions with unstable geologic conditions, especially Hanoi and Ho Chi Minh cities. When huge projects such as high-rise buildings, super–high buildings with 4-6 basements, and subway are constructed, foundation pits need to be excavated down from several to tens of meters. The diaphragm walls of foundation pits are usually kinds of temporary ones as Larsen steel plates or types of permanent ones as continuous barrette piles lying underground [1, 2]. The displacements of diaphragm walls have to be monitored while constructing pits to prevent incidents [3]. Nowadays, a popular solution for observation is geodetic methods (i.e., to observe the movement on the top of diaphragm walls) and geotechnical methods using inclinometer sensors (i.e., to monitor the displacement according to the depth direction of the diaphragm walls). The advantage of geodetic methods is that the absolute displacement can be obtained at high accuracy.

In contrast, a disadvantage is that they can only detect the displacement at the top points of the diaphragm wall. The advantage of the inclinometer geotechnical method is monitoring the displacement of diaphragm walls according to the depth for early warning and giving timely handling solutions. However, inclinometer displacement values are relative because the original point chosen for comparison is at the bottom of the guide pipe, which is deeply under the ground and difficult to observe. Additionally, with the weak geological background, the bottom point is unstable, and thus the observed values reflect the displacement of diaphragm walls inaccurately.

There are several studies on this. Some documents mentioned the application of the inclinometer method in monitoring the diaphragm walls' displacement and emphasized the discrepancies between results from geodetic methods and inclinometer sensors [4, 5], or numerical modeling experimental monitoring for a full-scale diaphragm wall [6]. The displacement of diaphragm walls is the construction of the foundation pit in soft ground, which has been shown in [7, 8, 9, 10]. From the advantages and disadvantages of each method, it can be expected that the integrated solution of geodetic and geotechnical methods in deformation

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monitoring is a good choice [11].

In Vietnam, no studies have ever mentioned the combination of the inclinometer and geodetic methods. This article shows the research on the integrated solution to improve the reliability of the observation results in the construction of a deep excavation pit on soft ground. The integrated method has a great significance in which the displacement of the top point measured by an inclinometer has a significant deviation in theory. The observation results are used to recommend the construction team choosing a suitable regime of work later. Through an experiment in an actual project, it is concluded that the integrated solution is appropriate to monitor the diaphragm walls of a deep excavation pit when projects are constructed on the soft ground in Vietnam.

2. Monitoring the displacement of diaphragm walls by geodetic methods

Geodetic methods are usually used to monitor the horizontal displacement of points at the top of diaphragm walls. The nature of these methods is to determine the coordinates of observation points to obtain the displacement at different periods. The popular observation instruments are high precision total stations. Common surveying methods include triangulation, polygon, intersection, standard direction, and automatic monitoring using an electronic tacheometer in real-time [12]. The process of monitoring the horizontal displacement by geodetic methods is shown in Figure 1.

Observation results obtained by geodetic methods are absolute and high accuracy displacement values because the displacement of monitoring points is determined at stable benchmarks. However, the most significant disadvantage of this method is that it can only detect the displacement of the top points of diaphragm walls. In constructing a foundation pit, monitoring displacement of diaphragm walls according to the depth is essential because of its effect on the construction of the basement later. At present, the geotechnical method using inclinometer sensors is usually applied to monitor the diaphragm wall's horizontal displacement according to the depth.

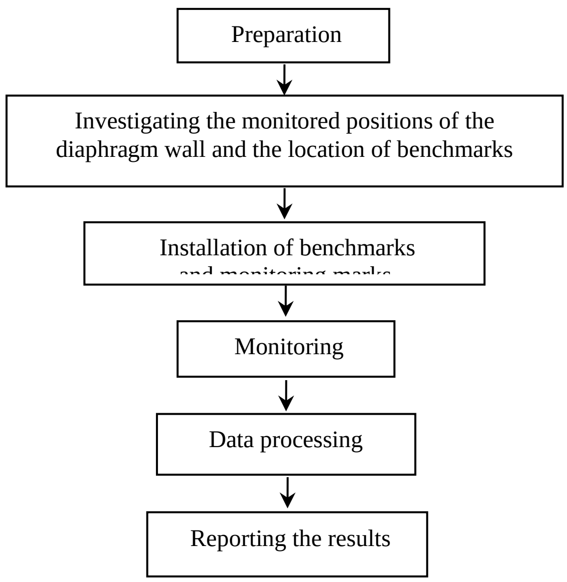

Fig. 1. The process of monitoring the horizontal displacement by geodetic methods.

3. Monitoring the horizontal displacement of diaphragm walls by geotechnical methods

3.1 Components of an inclinometer

The inclinometer device monitors the horizontal displacement of rock layers according to the depth in landslide areas and dykes, dams, transportation roads; to observe the horizontal deformation of the diaphragm walls and piles. The main components of an inclinometer are shown in Figure 2 (left and middle), including guide pipe (1), probe head (2), signal cable (3), and reading device (4). The cross-section of guide pipe is shown in Figure 2 (right).

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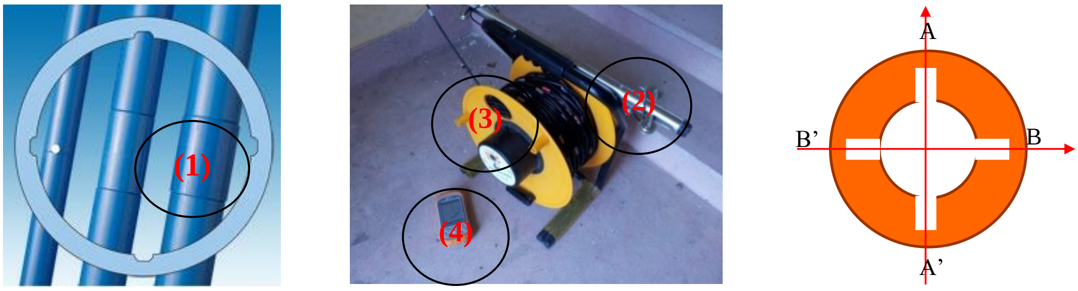

Fig. 2. An inclinometer device and the cross-section of guide pipe.

3.2. Principles of monitoring the horizontal displacement by an inclinometer

Monitoring the horizontal displacement by an inclinometer is a method that observes the displacement of objects indirectly through the movement of the guide pipe. When the diaphragm walls are the type of barrette, the guide pipe is installed inside the wall. If the diaphragm walls are Larsen steel sheet piles, the guide pipes will be installed outside those piles. The basic principle of monitoring the horizontal displacement by an inclinometer is that the point at the bottom of the guide pipe is used as the origin to calculate the displacement of the upper points. The displacement of the pipe is calculated in two perpendicular directions AA' and BB', with formulas shown in Figure 3.

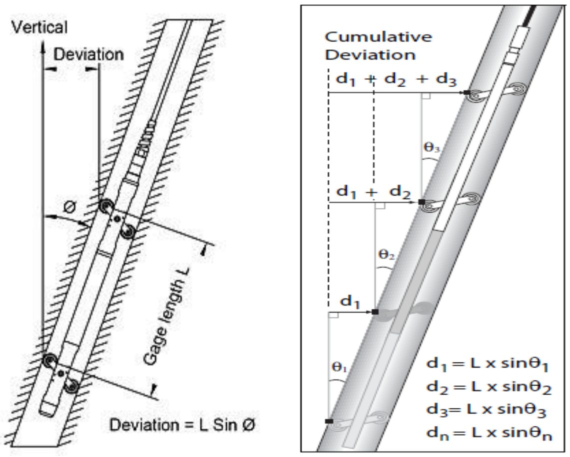

Fig. 3. Diagram of calculation in monitoring the horizontal displacement by an inclinometer.

The way to install the guide pipe and how to monitor by an inclinometer were mentioned in detail in literary studies, e.g., [1, 13, 14]. Monitoring of the horizontal displacement of diaphragm walls by an inclinometer has process shown in Figure 4.

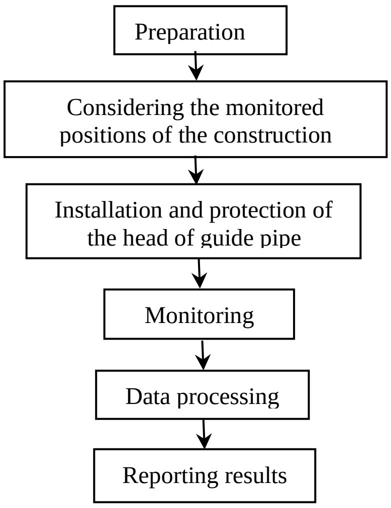

Fig. 4. Process of monitoring the horizontal displacement by an inclinometer.

As mentioned above, the displacement is compared with the reference point at the bottom of the guide pipe. In this case, the guide pipe was anchored to the original rock layer so that it had no movement, thereby without error. The higher the probe head moves, the bigger the observation error is; thus, the top of the guide pipe on the ground has the most significant error. According to device specifications provided by the producer, the reading head of the inclinometer is displayed to 0.01 mm. Each time the probe head moves 0.5 m in the guide pipe, the reading error is 0.25 mm. When the length of the guide pipe is 25 m, the accumulated error in one axis is 6 mm.

The geotechnical method using inclinometer sensors has advantages such as detecting the displacement in-depth and early warning about dangerous deformations of the diaphragm walls. Therefore, safety precautions are proposed as soon as the deformation begins, or there is even no deformation, and they will help solve any situations more simply and less expensively. However, the disadvantage is that it can only determine the relative displacement of the diaphragm wall at different depths compared with the original point at the bottom of the guide pipe. At this point, surveyors cannot observe it.

If the bottom point of the guide pipe is unstable, the observed values reflect the displacement of the diaphragm wall inaccurately. Thus, to accurately monitor the diaphragm wall's horizontal movement, the combination of inclinometer sensors with geodetic methods should be applied.

4. Integration of geodetic and geotechnical methods in monitoring the displacement of diaphragm walls

This article proposed an integrated approach to monitor the horizontal displacement of diaphragm walls in constructing a foundation pit to overcome the disadvantages of the two abovementioned methods. The objectives of the study are:

- If the bottom of the guide pipe (in the inclinometer method) is anchored to a stable rock layer, the integrated method helps to improve the precision of monitoring at the points located deeply inside the diaphragm wall. Because high accurate electronic total stations are used to survey the displacement of the top of the tube, the result is much better than the inclinometer-only measurement.

- If the bottom of the guide pipe is anchored to an unstable rock layer, the purpose of using the integrated method is to determine the movement of that bottom point and the accurate displacement values of points inside the diaphragm wall.

4.1. The bottom of the guide pipe is anchored to a stable rock layer

When the bottom of the guide pipe is attached to a stable rock layer, using the integrated solution helps to increase the accuracy of monitoring the horizontal displacement at points inside the diaphragm walls, and the surveying plan, in this case, is shown as follows:

- Put a cap on the top of the inclinometer tube and draw two rectangular coordinate axes (Fig. 5). The distances from the center point to all points on the axes (A, B, C, D) are measured by a ruler accuracy of ±0.1 mm. The A-B axis coincides with A0-A180, and the C-D axis is B0-B180 of the guide pipe.

In each period, the horizontal displacement is measured in-depth by an inclinometer and the center point on the guide pipe's top. Thus, this point has two displacement values. Displacements were surveyed in the geodetic coordinate system $q^{(o)}_{X_{TD}}$, $q^{(o)}_{Y_{TD}}$ and the values were obtained in the inclinometer coordinate system $q^{(o)}_{X_{ICL}}$ $q^{(o)}_{Y_{ICL}}$ (Fig. 6).

Based on Figure 6, the formula of transformation of coordinates between the two systems (i.e., from the geodetic coordinate system to the inclinometer coordinate system) for the center point on the top of the guide pipe is established as follows:

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Fig. 5. Designation of a lid whose center point coincides with the center of the guide pipe.

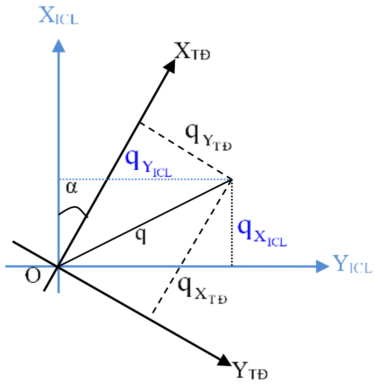

Fig. 6. Coordinate systems in monitoring the displacement by geodetic and inclinometer methods.

$$\left.\begin{aligned} q^{(o)}_{X_{TĐ-ICL}} &= q^{(o)}_{X_{TĐ}}.\cos\alpha - q^{(o)}_{Y_{TĐ}}.\sin\alpha \\ q^{(o)}_{Y_{TĐ-ICL}} &= q^{(o)}_{X_{TĐ}}.\sin\alpha + q^{(o)}_{Y_{TĐ}}.\cos\alpha \end{aligned}\right\} \tag{1}$$

where $q^{(o)}_{X_{TĐ}}$, $q^{(o)}_{Y_{TĐ}}$ measured by the geodetic method are the displacement values of the point at the top of the guide pipe (O) in the geodetic coordinate system;

$q^{(o)}_{X_{TĐ\text{-}ICL}}$, $q^{(o)}_{Y_{TĐ\text{-}ICL}}$ measured by the geodetic method are the displacement values of the point on the top of the guide pipe in the inclinometer coordinate system;

α is the rotation angle between the geodetic coordinate system and the inclinometer coordinate system (Fig. 6).

Thus, on the top point of the tube, two displacement values were observed by the two devices with different accuracies. Because of higher accuracy, the values surveyed by the geodetic method are considered the actual displacement. The difference between the two types of observations is called the error of closure of monitoring by the inclinometer. The following equation calculates the errors of closure in coordinate axes:

$$\left.\begin{aligned} \omega^{(o)}_{X} &= q^{(o)}_{X_{ICL}} - q^{(o)}_{X_{TĐ\text{-}ICL}} \\ \omega^{(o)}_{Y} &= q^{(o)}_{Y_{ICL}} - q^{(o)}_{Y_{TĐ\text{-}ICL}} \end{aligned}\right\} \tag{2}$$

In Eq. (2), $q^{(o)}_{X_{ICL}}$, $q^{(o)}_{Y_{ICL}}$ were observed by the inclinometer in the corresponding coordinate system and are displacements of the top point of the tube.

According to the principles of monitoring and calculating the horizontal displacement in the inclinometer method, it is easy to realize that the points close to the reference point have higher accuracy than the far ones. It means the accuracy of the upper points is worse than that of the lower ones, and the top point of the tube has the most significant error. The series of observations are adjusted by distributing the error of closure of the center point on the top of the guide pipe to all points. This is conducted relying on the principle of proportion to the height. From that the adjusted data of the displacement values are calculated:

$$\left.\begin{aligned} q^{(i)}_{X_{ICL\text{-}TĐ}} &= q^{(i)}_{X_{ICL}} - \frac{H_i}{H}\omega^{(o)}_{x} \\ q^{(i)}_{Y_{ICL\text{-}TĐ}} &= q^{(i)}_{Y_{ICL}} - \frac{H_i}{H}\omega^{(o)}_{Y} \end{aligned}\right\} \tag{3}$$

where $q^{(i)}_{x_{ICL}}$, $q^{(i)}_{Y_{ICL}}$ are the displacements of the point i that were monitored by the inclinometer at the height H_i, $q^{(i)}_{X_{ICL-TĐ}}$, $q^{(i)}_{X_{ICL-TĐ}}$ are corrected displacements of the point i, H_i, H are the heights of the monitoring point i and the top point of the tube, calculated from the pipe's bottom point.

4.2. The bottom of the guide pipe is anchored to an unstable rock layer

As mentioned above, displacement values are calculated in a coordinate system with the reference point at the guide pipe's bottom. Therefore, when this original point is unstable, the observed values are inaccurate. It is difficult to directly observe the displacement of this bottom point, so it is necessary to choose another reference point that can be located quickly by a geodetic method. The new reference point is the center of the top of the inclinometer guide pipe on the ground. Fortunately, the inclinometer device has the associated software to calculate the displacement of monitoring points in a system, with the reference point at the top of the guide tube. Therefore, the reference point must be chosen again on the guide pipe's top in the calculation procedure. Then, displacement values $q^{(i)}_{X_{ICL}}$ and $q^{(i)}_{Y_{ICL}}$ of all points inside the diaphragm wall are calculated. Although all points on the top of the guide pipe are unstable, their displacements can be surveyed using a geodetic method [15,16], e.g., a total electronic station. Thus, in each monitoring period, the center of the top of the guide pipe has to be located precisely in the geodetic coordinate system. The difference of coordinates between the two periods is the displacement values $q^{(o)}_{X_{TĐ}}$ and $q^{(o)}_{Y_{TĐ}}$ of the center point.

The conversion calculation of the displacement values of the top of the guide pipe from the geodetic coordinate system to the inclinometer coordinate system can be conducted using eq. (1) by which the values $q^{(o)}_{X_{TĐ-ICL}}$ and $q^{(o)}_{Y_{TĐ-ICL}}$ are determined. The coordinates which were surveyed by geodetic methods have high accuracy, so the displacements of the top of the tube $q^{(o)}_{X_{TĐ-ICL}}$, $q^{(o)}_{Y_{TĐ-ICL}}$ are considered to be actual values (i.e., without error) and are used to rectify in inclinometer observations $q^{(i)}_{X_{ICL}}$, $q^{(i)}_{Y_{ICL}}$ as the following equation:

$$\left.\begin{aligned} q^{(i)}_{X_{ICL-TĐ}} &= q^{(i)}_{X_{ICL}} + q^{(o)}_{X_{TĐ-ICL}} \\ q^{(i)}_{Y_{ICL-TĐ}} &= q^{(i)}_{Y_{ICL}} + q^{(o)}_{X_{TĐ-ICL}} \end{aligned}\right\} \quad (4)$$

5. Experiment

To verify the proposed approach, an experiment combining an inclinometer with geodetic methods is established. This is to monitor the displacement of the diaphragm wall of a high building with two basements in Ho Chi Minh city. The experiment is conducted at the time of construction of the underground part (the underground part is constructed by the semi-top down method). The observation points on the diaphragm wall are eight (denoted by P01, P02, P03, P04, P05, P06, P07, P08). The depth of the diaphragm wall is 20 m. The guide pipe for inclinometer monitoring is a specialized plastic tube (D70) of the slope indicator installed inside the steel pipe D114 (the D114 tube was fixed by concrete mortar without shrinking inside the diaphragm wall in the phase of construction). The A axis of the guide pipe is perpendicular to the diaphragm wall, while the B axis is parallel to the diaphragm wall. On the top of the guide pipe, there is a lid (Fig. 5) for monitoring the horizontal displacement of the center point by the geodetic method.

Steps of monitoring in the experiment are:

- Monitoring the displacement of the diaphragm wall in depth by the GK-604D-50m inclinometer device of the American Geokon manufacturer;

- The horizontal displacement of the center point on the top of the tube is surveyed by the geodetic method as follows:

+ Establishment of the geodetic coordinate system that the X and Y axes are respectively parallel to the A and B axes of the inclinometer;

+ Three benchmarks were drilled down 40 m in the surrounding area;

+ The total station TCR1201+ is used that has an accuracy of angular measurement $m_\beta=\pm 1.0''$ and an accuracy of distance measurement $m_S=\pm(1+1.5D)$ *mm*, D is the length of the edge in kilometer;

+ A network is established between the three benchmarks and the monitoring points. All angles and edges are then measured. The coordinates of the observation points are calculated after the adjustment of the network in two periods. The benchmarks are stable, and the mean square error of position m_P of all observation points is less than 2 mm.

Using the calculation process of the integrated solution in two cases of the bottom point of the guide pipe: stability and instability at P05 in two periods. Results are as follows:

+ The displacement of the center at the top of the pipe is measured by an inclinometer (its bottom point is the reference point): 30.97 mm on axis XICL and 0.27mm on axis YICL.

+ The displacement of the center at the top of the pipe is measured by the geodetic method: -24.30 mm on axis XTD and -1.10 mm on axis YTD.

The first case: Assume that the bottom of the inclinometer guide tube is stable:

When the geodetic method is used to monitor the displacement, the mean square error of the position has very high accuracy ($m_P < 2.0$ mm); it can obtain the absolute displacement values because of the stable benchmarks. Therefore, the displacement of the center point on the top of the tube is the actual value. Based on the displacement results, the error of closure is calculated as Eq. (2) with the obtained results of -6.67 mm and 1.37 mm. The closure errors are distributed to all points inside the guide pipe using Eq. (3), so their displacement values are more accurate. Table 1 shows the inclinometer displacement values after the error of P05 is corrected.

Tab. 1. The inclinometer displacement values after correcting the error (point P05).

The monitoring depth (m)	The inclinometer displacement values (mm)		Correction number according to pipe length ratio (mm)		The integrated displacement values (mm)	
	$q^{(i)}_{X_{ICL}}$	$q^{(i)}_{Y_{ICL}}$	$\frac{H_i}{H}\omega^{(o)}_X$	$\frac{H_i}{H}\omega^{(o)}_Y$	$q^{(i)}_{X_{ICL-TD}}$	$q^{(i)}_{Y_{ICL-TD}}$
0.0	-30.97	0.27	-6.67	1.37	-24.30	-1.10
0.5	-30.33	0.44	-6.50	1.34	-23.83	-0.90
1.0	-29.62	0.47	-6.34	1.30	-23.28	-0.83
1.5	-28.97	0.49	-6.17	1.27	-22.80	-0.78
2.0	-28.39	0.50	-6.00	1.23	-22.39	-0.73
…	…	…	…	…	…	…
18.0	-6.02	-0.26	-0.67	0.14	-5.35	-0.40
18.5	-4.45	-0.32	-0.50	0.10	-3.95	-0.42
19.0	-2.89	-0.29	-0.33	0.07	-2.56	-0.36
19.5	-1.51	-0.15	-0.17	0.03	-1.34	-0.18
20.0	0.00	0.00	0.00	0.00	0.00	0.00

After all the observation values were corrected for their errors, we could draw a chart of axial displacement. Figure 7 shows the diagram of the P05 position before and after the error is corrected. It shows the inclinometer displacement values according to the depth of the diaphragm wall (the graph line of measuring by inclinometer) and the values with improved accuracy after the inclinometer sensor is integrated with the geodetic method (the graph line of measuring by integration of the inclinometer and geodetic methods).

The second case: Assume that the bottom of the inclinometer guide tube is unstable:

The point at the bottom of the tube is the source. Thus, the inclinometer displacement values of the point at the top of the pipe must be added with the source's displacement value. As mentioned above, the monitoring results by the geodetic method have high accuracy ($m_p < 2.0$ mm), which are determined from stable benchmarks. Thus, the displacement of the center point at the top of the pipe is considered the actual value. The inclinometer observed values are recalculated when the reference point is at the top of the pipe. The geodetic displacement values that are transformed to the inclinometer coordinate system are corrected in all inclinometer values as Eq. (4). The updated results of P05 are shown in Table 2.

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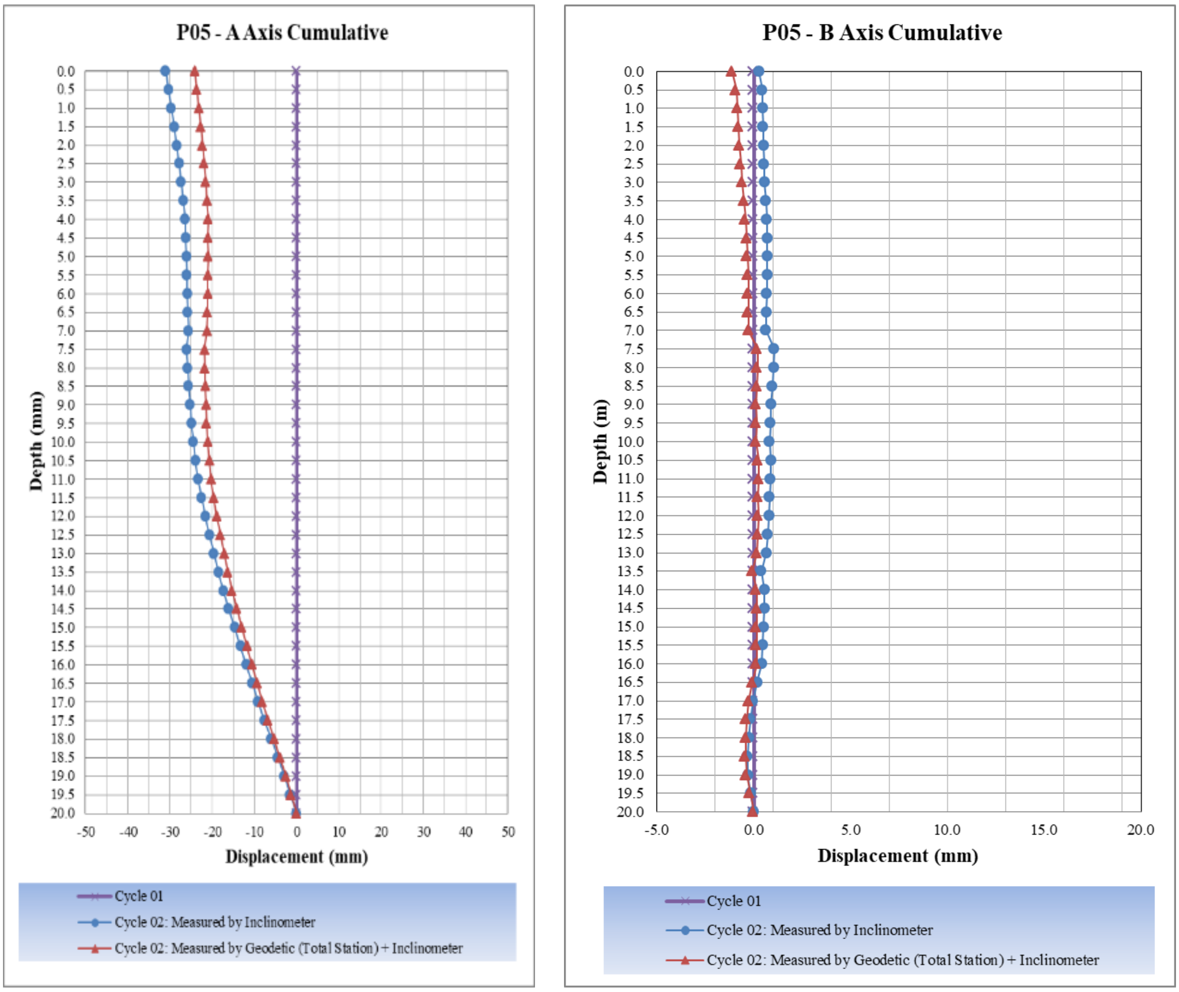

Fig. 7. Charts of P05 observation points before and after correcting the error.

Tab. 2. Displacement values of all observation points measured by the inclinometer after correcting the displacement of the origin.

Monitoring depth (m)	Inclinometer displacement values (mm)		Correction number (mm)		Integrated displacement values (mm)	
	$q^{(i)}_{X_{ICL}}$	$q^{(i)}_{Y_{ICL}}$	$q^{(o)}_{X_{TD-ICL}}$	$q^{(o)}_{Y_{TD-ICL}}$	$q^{(i)}_{X_{ICL-TD}}$	$q^{(i)}_{Y_{ICL-TD}}$
0.0	0.00	0.00	-24.30	-1.10	-24.30	-1.10
0.5	0.64	0.17	-24.30	-1.10	-23.66	-0.93
1.0	1.35	0.20	-24.30	-1.10	-22.95	-0.90
1.5	2.00	0.22	-24.30	-1.10	-22.30	-0.88
2.0	2.58	0.23	-24.30	-1.10	-21.72	-0.87
…	…	…	…	…	…	…
18.0	24.95	-0.53	-24.30	-1.10	0.65	-1.63
18.5	26.52	-0.59	-24.30	-1.10	2.22	-1.69
19.0	28.08	-0.56	-24.30	-1.10	3.78	-1.66
19.5	29.45	-0.42	-24.30	-1.10	5.15	-1.52
20.0	30.97	-0.27	-24.30	-1.10	6.67	-1.37

Table 2 and Figure 8 indicated that the integrated solution can monitor the displacements of all points inside the diaphragm more accurately. In this solution, the origin at the top of the tube is chosen.

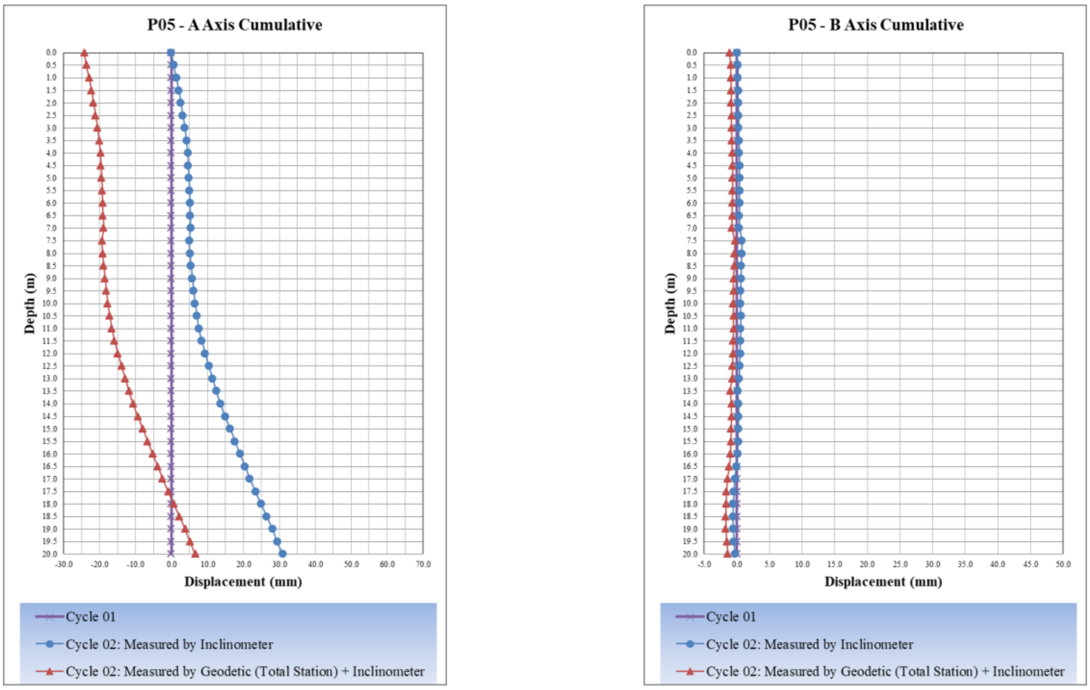

Fig. 8. Charts of P05 point before and after correcting the displacement of the origin.

6. Discussions

In the geotechnical method using inclinometer sensors, the origin is the guide pipe's bottom point, and it is difficult for surveyors to observe. Therefore, this method only determines the relative displacement values of points at different depths inside the diaphragm wall. If the bottom point of the guide pipe is unstable (e.g., because it is installed in the soft ground), the observed values will inaccurately reflect the level of displacement.

The geodetic method can survey the displacement of the center point on the top of the tube with high accuracy, with an error of position less than ±2.0 mm. Additionally, it can obtain the absolute displacement values.

When an inclinometer is integrated with geodetic methods, the obtained displacements are absolute values. Suppose the guide pipe is not anchored to a stable rock layer. In that case, it is necessary to combine the inclinometer with the geodetic method in monitoring the horizontal displacement of diaphragm walls to achieve more accurate results. In contrast, when the inclinometer guide pipe is attached to a stable rock layer, an inclinometer is used to measure the displacement. Additionally, in some periods, geodetic methods should also be used to check and correct the inclinometer displacement values. This is to impvove the reliability of the derived displacement and to avoid costing money.

7. Conclusion

The integration of geodetic methods and inclinometer sensors in monitoring the horizontal displacement of the diaphragm wall of a deep excavation pit on the soft ground helps advance precision of observation (the bottom of the guide pipe is attached to a stable rock layer). In the experiment conducted in this article, the displacement values between the two methods are -6.67 mm on the X-axis and +1.37 mm on the Y-axis.

Choosing the center at the top of the pipe to be the origin for determining precisely displacement of points in the diaphragm wall is allowed. However, if the displacement measured by the inclinometer is smaller than in theory, it is unnecessary to observe geodetic methods.

This integrated method has a good efficiency in monitoring the displacement of diaphragm walls on the soft ground, especially when the center of the bottom of the pipe measured by an inclinometer is unable to affirm the stability to choose as a reference point.

The integrated method can be applied for monitoring different works, such as irrigation-hydroelectric dams, excavation pits, retaining walls, landslides, mining, or in areas with leveled foundations. It is necessary to carefully study the geological engineering documents and the design of the diaphragm wall before deciding to combine geodetic and geotechnical methods to avoid costing money and time.

8. Acknowledgments

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