Displacement Mapping of Point Clouds for Retaining Structure Considering Shape of Sheet Pile and Soil Fall Effects During Excavation

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**Abstract:** The entire large-scale retaining structure can be monitored by simulating a three-dimensional point cloud obtained by laser scanning. The behavior of the retaining structure composed of sheet piles according to excavation was analyzed by the displacement mapping method in this paper. The displacement errors can be generated due to inclined sections, U-shaped protrusions of sheet piles and cutting point clouds, and fall and deposition of soil adhering to the sheet pile. Therefore, the analysis error was minimized by pre-treatment of the point cloud considering the shape of the sheet pile before displacement mapping. For displacement mapping, the C2M (Cloud to Mesh) distance was calculated by segmenting the point cloud of the retaining structure into 5 rows and 20 columns, which have about 100 elements. Analysis of the seven monitoring results during day 0 to day 35 was performed, and the maximum displacement occurrence point and the expansion of displacement with the time were evaluated by displacement mapping. In an in-depth analysis after displacement mapping, it was possible to estimate the displacement variation in the vertical direction of a pile in which the excessive displacement occurred as well as the change pattern of the displacement in the horizontal direction of the entire pile head. The crack was found at the top of a sheet pile occurred excessive displacement, which was verified by the visual inspection.

***Key words***: Displacement mapping, Retaining structure, 3D Laser scanning, Sheet pile, Point cloud

1. Introduction

The retaining structure is constructed to prevent the collapse of the ground due to the excavation. The displacement due to excavation can be reduced by driving the sheet piles to the ground before excavation (Tan and Paikowsky (2008), Cherubini (2000), Bilgin (2010), Woo and Salgado (2015)). The shaft resistance between soil and grouting can be generated during the movement of soil (Salgado et al. (2000), Salgado et al. (2015), Han, et al. (2017)). When reinforcing materials such as soil nailing and anchors are used as reinforcement materials with sheet piles, pre-stress can be applied before excavation to improve the constraining stress of the retaining structure, as well as minimize the stress release of the ground due to excavation (Anderson et al. (1983), Zhao et al. (2014)).

It is important to control the displacement of the sheet pile head during excavation in the retaining structure. If the excessive displacement occurs in a specific area, the displacement must be restored immediately with the reinforcing method. The displacement measurement technologies, such as inclinometer, extensometer, and total station have been used to measure the displacement of retaining structure (Allen et al. (2002), Benjamim et al. (2007), Ma et al. (2018)). However, since these methods can measure the displacement only at the point where the monitoring is performed, the structure can be failed if excessive displacement occurs at an area where the sensors are not installed. Recently, research has been conducted on monitoring by photogrammetry and a drone-based orthoimagery (Scaioni et al. (2014), Hain and Zaghi (2020), Jiang and Bai, 2020). However, in the retaining structure, displacement of 1 mm or 0.1 mm is generated every day due to the excavation, and the resolution of the image is not high to monitor it. But it is difficult to secure accuracy as a displacement monitoring technique. Research to detect local damages in geotechnical structures by thermal infrared cameras was also perforemed, but displacement estimation is not available (Maguire, et al., 2018; Seo et al., 2017). Soga et al. (2015) studied the application of a BOTDR (Brillouin Optical Time Domain Reflectometry)-based distributed fiber optic sensor that can permanently monitor large-scale structures. In this paper, 3D laser scanning was used as a monitor technology to scan the entire large-scale structure, such as the retaining structure. Laser scanning has been mainly used in civil engineering as a technique that simulates and utilizes three-dimensional shapes, such as BIM (Building Information Modelling) (Brilakis et al. (2010), Randall (2011), Bosché et al. (2015)). In recent years, the laser scanning technology is also used as a monitoring technique due to the improvement of the accuracy and analysis method of laser scanning. Research in which laser scanning is applied to the monitoring of various infrastructures such as bridges, tunnels, and piles has been performed (Olsen, et al., 2010; Riveiro et al., 2016; Yang et al., 2017; Luo et al., 2020). However, since it has not enough accuracy in the structures having a small displacement, it is necessary to study to increase the accuracy by developing various analysis methods. Since numerous points discontinuously represent an object in the point cloud, the resolution causes a major error in the displacement calculation. The Cloud to Could (C2C) comparison method, which directly compares points and points, is most affected by resolution. Techniques such as Cloud to Mesh (C2M), which can calculate the distance after representing the point cloud as a mesh, was developed to minimize the effect of resolution (Brodu and Lague, 2012; LAGUE et al., 2013; Acikgoz et al., 2017). The displacement calculation result of the point cloud is affected by the roughness or curvature of the object. Therefore, if an object has a curved or rough surface, it is necessary to compensate for the shape of the surface in the displacement calculation. Seo (2021) conducted a study analyzing the roughness and curvature of the failure surface of pile samples. Zhao et al. (2021) calculated the displacement of the retaining structure by displacement mapping for sheet piles, but the calculated displacement contained a displacement calculation error because the shape of the pile and the effect of soil fall was not be removed. However, in this paper, not only the analysis of roughness and curvature, but also the study of estimating the displacement by removing them was conducted. Therefore, it is possible to remove the effects of the inclined area, curved area, and soil fall of the sheet pile, which may cause errors in the point cloud displacement analysis, and improve the accuracy of the displacement calculation.

Laser scanning can collect a three-dimensional point cloud of a large-scale structure. In this paper, point clouds were acquired by laser scanning seven times for 35 days during the excavation period. After pre-treatment of the point cloud in consideration of the shape, it was divided into about 100 elements to perform displacement mapping. Therefore, during the monitoring period, it was possible not only to estimate the displacement variation of the entire retaining structure, but also to evaluate the local displacement.

2. Site Introduction and laser scanning

2.1. Excavation site conditions

Because stresses can be concentrated at the corners of the retaining structure during excavation, the stability at the corners of the retaining structure was evaluated in a large-scale excavation site excavating an area of 5.6 ha in this paper. Since excavation of over 200 m in the horizontal direction was conducted on both sides of the corner of the retaining structure, the behavior of the retaining structure at the corner has to be estimated. As shown in Figure 1a, while the excavation area was excavated, 3D laser scanning was performed to monitor the entire retaining structure at the corner. The length of the retaining structure at the corner where the monitoring was conducted is about 30m. Figure 1b shows the site before the excavation when first laser scanning was performed. Only the sheet pile head is exposed to about 1m from the ground, and the previously installed sheet pile appears according to the excavation. The excavation was carried out by excavators, and excavation proceeded to 6m from the ground surface (see Figure 1c). A sheet pile with a length of 17.5m and a width of 1.5m was constructed before the excavation, and 20 piles were interlocked with each other to create a retaining structure at the corner. A 22m long ground anchor was installed at a point about 1.0 m from the ground surface, and 20 anchors were linked each other through H beams. Anchors are installed equally at the 6m level after completing the excavation and then they were connected with H beams. Therefore, the lateral movement of the retaining structure due to the excavation is constrained by the prestress of the anchor and the sheet pile (see Figure 1d). In this paper, the retaining structure located at the corner was globally monitored under such excavation and reinforcement conditions as shown in Figure 1.

2.2. Monitoring of laser scanning on site

The stability of the retaining structure is not entirely evaluated by the existing monitoring technology in large-scale excavation site. The sensors are installed intensively by selecting the area where excessive displacement is expected. Therefore, if a large displacement occurs in an area where the sensor is not installed, it leads to the failure of the structure. As shown in Figure 2a, the displacement of a retaining structure was measured the displacement at the point where the total station target was installed on the pile head. However, the displacement monitoring of the entire retaining structure was performed by the 3D laser scanning with a resolution of 1.6 mm at 10m in this paper. Therefore, one point of the point cloud collected by laser scanning can achieve the same effect as one total station target, and it is possible to analyze the overall displacement of the retaining structure that simulates the three-dimensional shape of the entire sheet pile of the point cloud. Laser scanning was performed at three locations to scan the 30 m retaining structure located at the corner. A laser scanner, Leica P40 model, was used in this paper having the accuracy range of 1.2 mm + 10 ppm over full range and a resolution was set as 1.6 mm at 10 m in the field monitoring. The total station monitoring result was compared with the laser scanning result of the fifth sheet pile to determine the applicability of laser scanning as a monitoring technique. When the first day of laser scanning was set to day 0, a total of 7 laser scanning was performed on day 19, day 20, day 22, day 27, day 29, and day 35 to evaluate the behavior of the retaining structure according to the excavation. The excavation was completed on day 19 Therefore, only the sheet pile head can be analyzed from the scanning collected on day 0, and the behavior of the entire sheet piles can be analyzed from the scanning data collected after day 19. The displacement mapping was performed from day 19 after the excavation was completed, and the displacement analysis of the pile head was conducted from day 0. Target scanning was performed with 12 reference targets installed as shown in Figure 2b to display point clouds scanned at different locations and dates in one coordinate system.

2.3. Registration of point clouds

Figure 3 shows examples of the point clouds of the retaining structure collected by laser scanning. All point clouds were registered in one coordinate system by using the reference target coordinate. Unnecessary points, such as the ground and structures around the sheet piles, are cut out from the analysis, and only the retaining structure is left. Since the point cloud of day 0 is collected before excavation, only the head of the pile is represented as a point cloud as shown in Figure 3a. The point cloud collected on day 19 was able to be only scanned at scanning location 1 due to the constraints in the construction site. Therefore, the point cloud of a part of the retaining structure was not able to be obtained due to a shadowed area (see Fig. 3b). Figure 3c shows the point clouds collected on day 27, and point clouds were obtained from all three scanning locations without a shadowed area. Seo et al. (2021) verified that the C2M (Cloud to Mesh) analysis has higher displacement accuracy when C2M distance analysis is performed by selecting a point cloud with a high points density as a mesh. Therefore, C2M distance analysis was performed by meshing the point cloud acquired on day 27 that includes all sheet files with the highest resolution. In the point cloud collected on day 29, a shadowed area was generated by the construction machine in the field (see Figure 3d). Therefore, the point cloud collected on day 27 was used as the reference to compare point clouds before and after day 27 for C2M distance analysis.

3. Effect of Surface conditions in point cloud analysis

The displacement calculation of the retaining structure by analysis of the point cloud is influenced by the surface condition of the retaining structure. The sheet pile scanned in this paper has a smooth surface unlike structures with rough surfaces such as soil mixing walls (SMW). Therefore, an error that can occur due to the roughness of the surface can be minimized. However, if the C2M distance error that can occur depending on the shape and condition of the sheet pile surface is not considered, the displacement caused by excavation can be over or underestimated. Figure 4a shows a top view of a sheet pile which is divided into a flat section and an inclined section. If excavation occurs, the flat section will move perpendicular to the excavation, but the inclined section will move obliquely with the excavation. Therefore, the C2M distance between the reference mesh and the points can be calculated substantially equal to the actual displacement in a flat section. However, in the inclined section, the C2M distance can be underestimated than the actual displacement because the mesh calculates the C2M distance from the nearest point (see Figure 4b). Second, as shown in Fig. 4c, U-shaped protrusions are included in flat section of the sheet pile. In the C2M distance analysis, even if the inner surface of the protrusion is cut, residual points can be still existed. Both a point cloud and a mesh are placed on together for the cutting at the same time, but a comparing point cloud can be cut wider than the mesh due to the discontinuous point cloud. In this case, the displacement can be overestimated when comparing the mesh with the protrusions or widely cut points as shown in Figure 4d. Finally, since the excavation and laser scanning were monitored for 35 days, an attached soil can fall off from sheet piles (see Figure 4e). The surface of the sheet pile from which the attached soil was removed is mistaken for the sheet pile pushed in, which means the C2M distance is calculated in the opposite direction of the actual displacement. On the contrary, the pile can be mistaken for excessive displacement at the bottom of the pile due to the deposition of soil. (see Figure 4f). Therefore, it is necessary to minimize the influence of the shape and condition of the pile surface by analyzing the possible errors presented in Figure 4 before carrying out the displacement mapping.

Figure 5 shows the effect of an inclined section for calculating the C2M distance. Figure 5a shows a top view of two point clouds obtained on different days. If the white point cloud is meshed and compared with the red point cloud, the C2M distance of the points can be expressed as a histogram as shown in Figure 5b. The mean C2M distance is about 10.016 mm, but it can be seen that the results of the two sections are significantly different. Points in a flat section are predominantly distributed a part having a larger C2M distance than the mean C2M distance, but points having a displacement smaller than the mean C2M distance belongs to an inclined section. If only the flat section is cut in the red point cloud and calculate the C2M distance, a histogram can be obtained as shown in Figure 5c. The mean C2M distance of the flat section is 11.898 mm, which is about 1.882 mm larger than the mean C2M distance calculated by combining the two sections. If it is assumed that the displacement due to excavation occurs perpendicular to the excavation, the C2M distance of the flat section is close to the actual displacement. If only the red point cloud of the inclined section is compared with the mesh, the C2M histogram is calculated as shown in Figure 5d. The mean C2M displacement is about 7.459 mm, which is about 2.557 mm smaller than the mean C2M displacement calculated by combining the two sections. The C2M histogram calculated in Figure 5b is underestimated than the actual displacement due to the inclined section. Therefore, in this paper, only the flat section excluding the inclined section before analysis was used for displacement calculation in order to avoid the underestimation of the displacement due to the inclined area.

The Figure 6 shows an example of C2M distance analysis of point clouds obtained on day 27 and day 29. Figure 6a shows a point cloud cut only in the flat section of the sheet pile. In the front view and the side view, the points are very evenly distributed on the cut plane. If the point cloud collected on the day 27 is meshed and compared with the point cloud collected on day 29, the C2M distance result is obtained as shown in 'before cutting' of Figure 6b. Figure 6c shows a C2M histogram. The points outside the 'cutting area' in Figure 6b are the U-shaped protrusions and the points cut wider than the mesh so that the mean C2M is calculated as 0.440 mm, which has a difference of 43.2 % from the C2M distance of the maximum number of points () in the histogram. After removing the U-shaped protrusion and the points cut wider than the mesh, the C2M distances result only for the white points in the 'cutting area' picture of Fig. 6b is shown in Figure 6d and the mean C2M distance () is 0.689 mm, which has a difference of 11.2% from the C2M distance of the maximum number of points () in the histogram. This result is about 0.249 mm difference from the mean C2M distance evaluated by C2M analysis of the two point clouds together. The displacement can be underestimated by the points representing the U-shaped protrusion and the points cut wider than the mesh. The reason for this error is that the mean C2M distance of the cut outer points (the red points in the cutting area in Figure 6b) is -1.826 mm as shown in Figure 6e, which has a difference of 335.4% from the C2M distance of the maximum number of points () in the histogram. This value is calculated from a small number of points, but affects the total mean value. Therefore, a point cloud compared to the mesh was cut in a narrower area than a mesh in this paper, in order to minimize the influence of the U-shaped protrusion and the points cut wider than the mesh.

Finally, it is considered the effect of fall and deposition of soil adhering to the sheet pile during excavation in this paper. Figure 7 is an example of meshing the point cloud acquired on day 27 and comparing it with the point cloud acquired on day 0. As shown in Fig. 7a, the point cloud collected on Day 0 shows a distribution representing the attachment of residual soil. However, the point cloud collected on day 27 is represented a even surface of mesh as the attached soil falls off (see “before cutting” in Figure 7b). Because of the points representing the soil fall, the C2M distance histogram has many values that deviate from the normal distribution (see Figure 7c). The mean C2M distance is also about 2.016 mm, which is a big difference from the C2M distance indicating the maximum number of points in the histogram (). Since the C2M distance was calculated based on the points collected on day 27, the displacement due to excavation has to be a negative value, but it is a positive value. In this paper, it is assumed that the points outside the normal distribution in the C2M histogram are the points affected by the soil fall and were removed. Therefore, points out of the normal distribution are removed from the histogram of Figure 7c. When analyzing after removing the red point cloud of the 'cutting area' in Figure 7b, the mean C2M distance is -1.674 mm, which has a difference of 9.1 % from the C2M distance of the maximum number of points () in the histogram (see Figure 7d). The mean C2M distance has a result similar to the C2M distance indicating the maximum points in the histogram. The mean C2M distance between the point cloud of cut area and the mesh is about 4.041mm so that this result is the cause of having a positive value of the mean C2M distance in the analysis before cutting (). It can be seen that a large error occurs when soil falls or deposits from the sheet pile during laser scanning. Even as shown in the example of Figure 7, it can be mistaken that the displacement was not generated in the excavation direction, but the sheet pile was pushed into the excavation ground. Therefore, displacement mapping was performed after removing the effects of soil fall and deposition in this paper.

4. Displacement mapping of sheet piles

4.1. Pre-treatment of point clouds for displacement mapping

3D laser scanning can monitor a large-scale retaining structure entirely. In order to analyse the collected point clouds, the C2M distance analysis was performed by dividing the point cloud into 5 rows and 20 columns. The point cloud collected on day 0 analyzed only the pile head, and from day 19 when excavation was completed, the entire point cloud can be analysed so that it was divided into about 100 elements for the point clouds obtained each day as shown in Figure 8a. The point cloud collected on day 27, which has the highest resolution, was meshed and compared with other point clouds. Therefore, two point cloud analyses were performed in this paper as follows: the displacement behavior analysis of the pile head from day 0; and the displacement mapping of the entire retaining structure from day 19. As shown in Figure 8b, the point cloud of the sheet pile was divided into 1.0 m intervals, except for the area where the pile head and anchors were installed.

Zhao et al. (2021) conducted a study to find the damage of anchor in sheet piles by displacement mapping. However, the shape of the sheet pile and the surface condition of the sheet pile caused by the soil fall are not considered, and hence errors are included in the displacement results. Therefore, in this paper, factors affecting the displacement calculation errors are removed. Figure 9 shows an example of the point cloud analysis result in the column 14 of the point clouds obtained on day 27 and day 29. This result shows the effect of the shape and condition of the pile surface on the actual displacement analysis. In the first column corresponding to the pile head, the point cloud being compared was cut larger than the mesh, as shown in Figure 9a. Therefore, the mean C2M distance before cutting was overestimated as shown in the histogram results of Figure 9b. If the analysis is performed after removing the points outside the point cloud, the mean C2M distance is about 1.136 mm, which is 0.248 mm smaller than the calculated distance before cutting. In the second column, soil is attached to the elements of the mesh as shown in Figure 9c, but a even surface is represented by the point cloud after the soil fall off. The mean C2M displacement was 0.233 mm before cutting due to the effect of soil fall, but after removing the point cloud in this area, the mean C2M distance is 1.222 mm, which is 0.989 mm higher than before cutting. (see Fig. 9d). The effect of soil fall can greatly underestimate the actual displacement. The mean C2M distance is also underestimated in the third column as some points were cut larger than the mesh, resulting in negative C2M displacement (see Figure 9e). After removing these points, it is 1.141 mm, which is 0.181 mm more increased than before cutting (see Figure 9f). In the fourth column, it can be seen from Figure 9g that some points deviate from the mesh, but are hardly affected by the shape and condition of the pile surface. The difference in mean C2M distance before and after cutting was also the smallest at 0.077mm (see Figure 9h). In the fifth column, soil fall occurred in a large area as shown in Figure 9i. It clearly shows the area in the mesh where the soil is attached. Therefore, the mean C2M distance was calculated as -2.376 mm, but after removing the points affected by soil fall, the distance increased significantly to 1.050 mm. Therefore, when the soil attached to the sheet pile falls during the monitoring period, it has a great influence on the displacement calculation. If the analysis is performed without considering the shape and condition of the pile surface, the behavior of the pile displacement is not able to be properly analyzed as shown in the results before cutting in Figure 9k. However, if the analysis is performed after the pre-treatment of the point cloud in consideration of the shape and condition of the pile surface, the displacement is decreased regularly according to the depth of the pile.

Figure 10 shows an example of meshing the point cloud obtained on day 27 in Colum 14 and comparing it to the point cloud obtained on other days. Since the density of the point cloud obtained on day 27 is higher than others, it is converted into a mesh to compare it with other point clouds. Figure 10a is a result of comparing the point cloud on day 0 and the mesh on day 27. As the point cloud is located behind the mesh, the average C2M distance has a negative value. Conversely, the point cloud obtained on day 35 is located in front of the mesh so that the average C2M distance has a positive value. Therefore, it is reasonable that the displacement due to excavation has a negative value before day 27 and a positive value after day 27. Since the result obtained by converting the point cloud obtained on day 27 to a mesh has both positive and negative values, the displacement was recalculated based on day 0 for the displacement analysis of the pile head. Since not all sheet piles were excavated before day 19 day, displacement mapping of the entire retaining structure is not able to evaluate. Therefore, displacement mapping was performed by comparing the point cloud of day 19 with point clouds measured later.

4.2. Displacement analysis of pile head

In order to verify the applicability of laser scanning, the total station analysis result and the displacement calculation result of the pile head at fifth column were compared with each other as shown in Figure 2a (see Fig. 11a). The laser scanning results show a constant increasing pattern from day 0 to day 35. The total station results are similarly increased, which shows that laser scanning can be applied to the displacement monitoring of the retaining structure during excavation. Figure 11b shows the displacement analysis result of the entire sheet pile wall head over time. The maximum displacement of the pile head occurred at the fourteenth pile located at 21m. The displacement continued to increase after the 19th day and when the excavation was completed, approximately 15.289 mm of displacement occurred after day 0. Since the monitored retaining structure is located at the corner, both side walls act as constraints. Therefore, the increase in displacement is not large on both sides of wall after excavation is completed. However, it can be seen that excessive displacement occurred between day 0 and day 19 in the fifth pile head. As shown in Figure 11c, the H-beams on both sides of the fifth pile are disconnected from each other. Therefore, the fifth sheet pile was not moved as an integrated behavior by the H-beam, resulting in excessive displacement at the initial stage. The data in Figure 11b showed a significant increase between days 0 and 19. However, since there is an effect due to the long period of 19 days, in this paper, the displacement of sheet piles occurring per unit time was analyzed.

Figure 12a shows the increase in displacement after excavation at each pile head. The displacement of the fourteenth pile rapidly increased immediately after excavation, and only the sixth, eleventh, fourteenth, and sixteenth piles were compared in Figure 12b for in-depth analysis. For the sixth and eleventh piles with relatively small displacement, the increase in displacement is constant after the excavation is completed. However, the displacement is increased rapidly within 2 days immediately after excavation of the fourteenth pile with the maximum displacement and the piles around it. In Figure 12c, the rate of displacement increase is calculated between day 19 and 22 to understand in detail the pattern of the displacement increase in a short term immediately after the excavation. In the sixth pile, the rate of displacement increase between day 19 and 22 is maintained between 0.23 mm and 0.35 mm. However, the displacement of the fourteenth pile increased by 1.65mm during the same period, and it is more than two times compared to the 11th and 16th piles that are located around the 14th pile. Therefore, it is shown that not only the maximum displacement occurred around the fourteenth pile, but also the rate of the displacement increase is the most rapid immediately after excavation. The results of Figure 11b show that the fifth pile also has a large displacement, but when the displacement increase rate during the excavation period is observed, it shows a constant increase without a large increase (see Figure 12d). When comparing the results with the fourteenth pile, it was found that there is no significant increase in the displacement of the fifth pile immediately after excavation. Therefore, it can be seen that excessive displacement is not caused by the excavation.

4.3. Displacement mapping of retaining structure

In this paper, the displacement mapping method is applied to analyze point clouds of large-scale retaining structure obtained by 3D laser scanning. Based on day 19, each element of the point cloud collected on day 20, day 22, day 27, day 29, and day 35 was analyzed by C2M to determine the overall displacement change pattern of the retaining structure during the monitoring period. The point cloud data acquired before day 19 were excluded from the displacement analysis because the pile surface was not all exposed because it was before excavation. The displacement mapping result of day 20, one day after completing the excavation, shows that the overall displacement occurred at the bottom of the pile (see Fig. 13a) because the excavation at the bottom of the pile was completed on day 19. The displacement of the upper part is already reflected on the point clouds obtained day 19, and the displacement caused by the excavation of the lower part in sheet piles was reflected on the results of day 20. Comparing the displacement mapping results on day 22 with day 20, there is a rapid increase in displacement at the 13th and 14th piles (see Figure 13b). The displacement mapping result on day 27, which is the 8th day after displacement mapping, is shown in Figure 13c. The pile head displacement occurred at the 13th and 14th piles on day 22 was expanded to adjacent piles. The pattern of the extended displacement shows a positive parabola around the 14th pile. It can be seen that the increase in displacement is not significant at both edges of the retaining structure. Figure 13d shows the displacement mapping results on day 29, and the displacement that occurred at the 14th pile is not only expanded further, but also showed an increase in displacement at the 8th pile head. The displacement mapping result on day 35, which is the 16th day since the displacement mapping started, is shown in Figure 13e. Not only the displacement generated at the 8th pile is expanded, but the displacement generated at the 14th pile is also expanded, so that the two positive parabolas shapes representing displacement expansion are intersected each other. The two major displacements increasing area are expanded at different points on day 29, but a large single parabolic shape is created due to the intersection of these two parabolic shapes. Therefore, even if a local displacement occurs, the displacement area of the retaining structure is greatly increased due to the expansion and overlap of the local displacement area. As shown in Figure 13, displacement mapping using laser scanning can evaluate not only the displacement pattern of the local area, but also the stability of the entire large-scale retaining structure. After the displacement mapping is completed, reinforcement or detailed monitoring at specific areas where the excessive displacement has occurred is able to be applied.

After the displacement mapping is completed, the results for a specific pile are shown in Figure 14 for in-depth analysis. The excessive displacement is not monitored at tenth pile, but it can be representative to other piles behaviour to show the tendency of displacement change as shown in Figure 14a. For the first 3 days (day 19 to day 22) after displacement mapping, the displacement at the bottom of the pile is larger because the excavation near the bottom of pile was completed immediately before the monitoring. However, the displacement at the pile head starts to be larger on day 27 after 8 days of displacement mapping. The displacement variation on day 27 is maintained as the monitoring date increases and it is shifted by the displacement increase. The displacement change pattern at the point where no excessive displacement has occurred shows a similar tendency to that of the tenth pile. However, the fourteenth pile, where the maximum displacement occurred, shows a different pattern from other piles. The change pattern during the first three days of displacement mapping is similar, but the displacement of the pile head on the 27th day increases dramatically. The change in displacement is not large at the bottom of the pile after 3 days of displacement mapping, but a large displacement occurs at the top. Therefore, it is expected that the bending acting in the vertical direction is larger than that of other piles. The abrupt increase in displacement at the pile head is maintained until day 35 of monitoring. Therefore, a visual investigation was conducted at the top of the pile head, and crack was found at the upper part of the fourteenth pile head as shown in Figure 14c. Therefore, displacement mapping can specifically simulate the excessive displacement by detailed analysis in a specific area as well as the overall variation of the displacement in the retaining structure.

5. Conclusions

In this paper, 3D laser scanning was performed on the retaining structure composed of sheet piles. After pre-treatment of the point cloud considering the shape and condition of the sheet pile surface, displacement mapping was performed for the entire retaining structure. The detailed conclusions drawn by this study are as follows:

1) The sheet pile in the retaining wall is divided into an inclined section and a flat section. The displacement is underestimated by the inclined section in the C2M distance analysis so that the inclined section was removed. An error also occurred due to the larger cutting of point cloud than mesh and the U-shaped protrusion in the flat section and hence the error caused by these effects was removed. Finally, the displacement was under or overestimated by the fall and deposition of soil adhered to the sheet pile, and hence C2M analysis was performed after pre-treatment of this effect.

2) Laser scanning was performed seven times during 35 days, and the change in displacement of the pile head was analyzed. It was confirmed that excessive displacement occurred in the fifth and fourteenth piles. The results of the daily displacement rate analysis verified that the displacement of the fourteenth pile was caused by the excavation, and the displacement of the fifth pile occurred due to the disconnection of the H-pile at the fifth pile.

3) The laser scanner is able to collect the point cloud of the retaining structure entirely so that the displacement variation for the entire retaining structure was analyzed by the displacement mapping method. The point clouds of the retaining structure was divided into about 100 elements in 5 rows and 20 columns. Displacement mapping was carried out from day 19 when excavation was completed. It was possible to globally analyze the displacement variation pattern of the retaining structure until day 35. It was estimated by displacement mapping that the displacement generated at the head of the eighth and fourteenth pile expanded with time. Eventually, the displacement patterns of the two extended positive parabolic shapes are overlapped each other to create a single parabolic shape.

4) Based on the displacement mapping result, it was evaluated that the sheet pile with the maximum displacement among the entire retaining structure was the fourteenth pile, and an in-depth analysis was conducted on this pile. Compared to the other piles, the fourteenth pile was found to have a more rapid increase in displacement at the top of the pile when three days after the excavation was completed. A crack in the upper part of the fourteenth pile was verified by field investigation.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request. (Point cloud data)

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