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Study on the suitable sensor locations for tilt monitoring of power transmission tower

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ABSTRACT: Due to recent extreme weather conditions, there have been many reports of damage to infrastructure. For example, two power transmission towers collapsed due to landslides in 2022. The landslides may not only cause the tower collapse but also cause the base displacement. The base displacement of only a several millimeters can generate secondary stress, resulting in member deformation and insufficient strength of the steel tower members. Therefore, the towers that are at risk of landslides are surveyed once a year to investigate the progress of base displacement. However, the on-site investigation creates other risks, such as delays in detection and accidents during the travel to the site. So, the authors have been developing the tilt monitoring system of the power transmission towers. In the tilt monitoring system, one tilt sensor is installed on each of the four main members of the tower. The progress of base displacement is monitored by checking whether the observed tilt change exceeds a set threshold. In the current system, the threshold value is tentatively set to be 0.05 degrees. This system has already been installed to about one hundred towers in the field. In this study, a full-scale experiment is newly conducted to examine the optimal installation location of the tilt sensors to monitor the base displacement. In this experiment, ten tilt sensors are placed on each of the four main members, and the sensitivities to the base displacement are examined in detail.

KEY WORDS: Transmission towers; Base displacement; Remote monitoring; Tilt sensor

1 BACKGROUND AND OBJECTIVE

Due to abnormal weather in recent years, there have been many disasters in Japan, such as landslides and river flooding caused by heavy rain. The heavy rains of July 2021 caused a large-scale mudslide on the embankment of Atami City, which is still fresh in our memory. At the time of the disaster, an observation station in Atami City, which was relatively close to the disaster site, recorded an accumulated rainfall of 488mm, the highest rainfall ever recorded in July in the local history [1]. This mudslide disaster led to revisions of fill regulations to ensure safety of fills and effective penalties. In addition, when heavy rainfall and flood warnings are issued, the Japan Meteorological Agency has begun to issue detailed evacuation information, but even so, many lives have still been lost.

Power transmission towers have also been damaged by heavy rains and landslides. Two transmission towers collapsed in 2022 due to landslides caused by heavy rainfall. Although there was no direct loss of life at that time, approximately 120,000 households experienced large-scale power outages. Damage caused by landslides on transmission towers also includes displacement of tower bases due to landslides in the vicinity of the towers. This base displacement of only a few millimeters can cause secondary stress from the base, resulting in member deformation and insufficient strength. If this base displacement is detected too late and progresses, the member will buckle, requiring large-scale repair work or reconstruction.

The management of towers where landslides are a concern is conducted once a year to check the progress of base displacement by surveying. However, there is a risk of on-site attendance and delay in detection. Therefore, the authors propose tilt monitoring to remove these risks. Figure 1 shows the operational image proposed by the authors. In the proposed method, tilt sensors are installed on the four legs of a transmission tower and single pipe piles driven near the collapsed soil surface, and the measured values are monitored remotely. When an abnormality is detected, an alert is sent out and the risk is assessed by analyzing the observed data.

Figure 1. Operational image diagram

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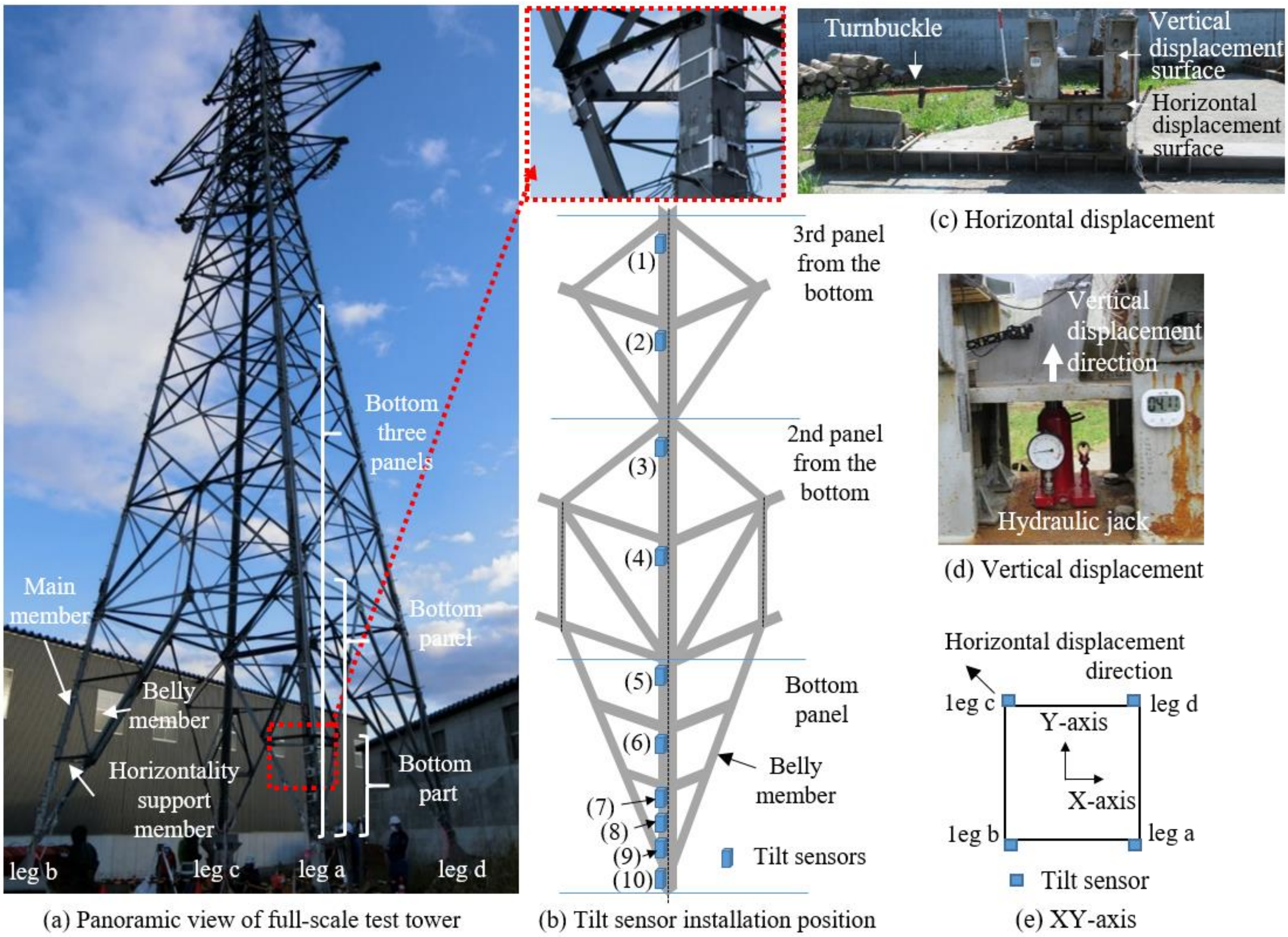

Figure 2. A full-scale test steel tower and test overview

This system is already in use on about 100 transmission towers in the real field. A provisional threshold value of 0.05deg is proposed based on the results of a full-scale test conducted previously. This value of 0.05deg corresponds to the allowable base displacement described in the non-statutory standard JEC-5101-2022 [2]. The allowable base displacement is defined by Equation (1), (2). In the equation, V is the allowable vertical base displacement, B is the distance between legs, and H is the allowable horizontal base displacement.

$$V[mm] = B[mm]/1200 \qquad (1)$$

$$H[mm] = B[mm]/800 \qquad (2)$$

Equation (1), (2) is not a legal requirement of the “Ministerial Ordinance Establishing Technical Standards for Electrical Equipment and Interpretation Thereof”. The equations are used as a control standard value for safety purposes [3].

In the test results previously conducted to calculate the above threshold values, the three tilt sensors installed on the same member had different sensitivity to tilt change [4]. This suggests that the sensitivity of tilt change may differ depending on the installation location, even for the same member. In this study, the number of tilt sensors was increased and retested, and the results indicated the best locations for observation.

2 PREVIOUS TEST RESULT

2.1 Overview of the test tower

The results of the previous test are presented here. Figure 2 (a) shows a full-scale test steel tower. This steel tower is made of L-shaped section steel, with a tower height of 28.20 m, a distance between legs of 6.08 m, and a tower weight of 10.3 tons. Generally, a transmission tower consists of main members, belly members, and support members. The main members and belly members are structural members, and the support members are designed as buckling stiffeners. For convenience of explanation, the legs of the tower are designated as leg a to leg d, as shown in the lower part of the photograph in Figure 2. The coordinate system xyz is set up with the center of the four legs as the origin, the x axis parallel to the ab plane (in the line orthogonal direction), the y axis parallel to the ad plane (in the line direction), and the z axis points upward perpendicular to the ground. Figure 2(b) shows the installation of the tilt sensor on one member, where all four legs are installed in almost the same way. The section from the ground to the connection between the horizontal members and the main member is called the bottom panel, and the section sandwiched between the belly members is called the panel. Since the influence of base displacement is generally

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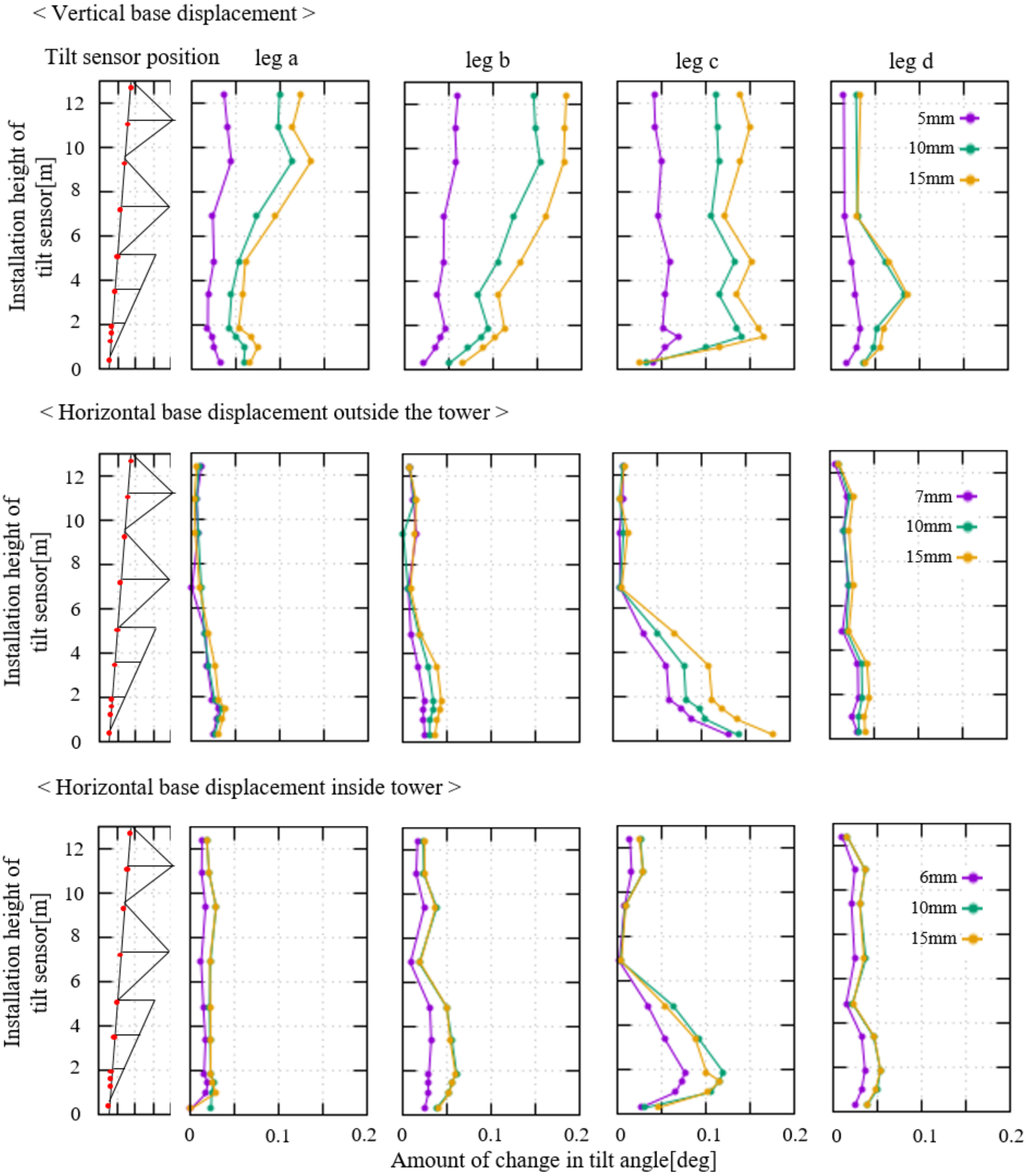

Figure 3. Relationship between tilt change and base displacement

considered to be limited to the third panel from the bottom, ten tilt sensors were installed per main member leg from the bottom to the third panel [5]. Since structural eccentricity due to joints may affect the tilt change at the lowest section, tilt sensors were installed at three locations to check. The tilt sensors near the member intersections could not be installed until a short distance from the intersections, so they were installed 10 cm lower from the intersections. The sensors measured tilt in the x-axis and y-axis directions with a measurement interval of 1 minute and a resolution of 0.0035 deg. The tilt sensor was glued to the member, and the top and bottom of the sensor were fixed with stainless steel bands.

2.2 Forced base displacement method

The three legs except leg c are completely fixed. Only leg c is a movable leg; leg c has vertical upward displacement and horizontal displacement at an angle of 45 degrees to the inside and outside of the tower. Figures 2(c) and 2(d) show how the forced base displacements were given. As shown in Figure 2(c), the fixed point is located approximately 2 m from the movable leg in the outward direction of the tower. A turnbuckle was fixed between that fixed point and the movable leg to provide

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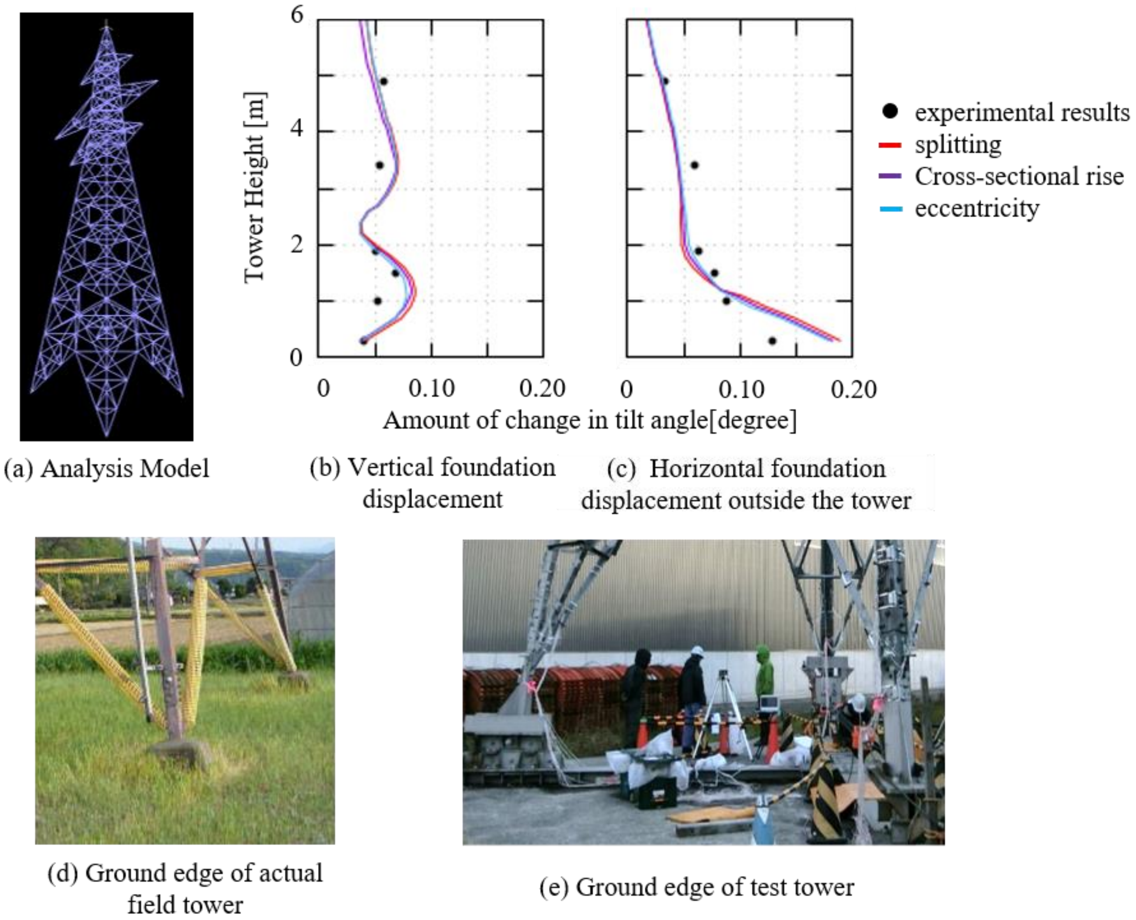

Figure 4. Analysis Model and Results

horizontal base displacement inward and outward. The horizontal displacement surface is not vertically constrained, so when the leg c is displaced horizontally, it may also be displaced vertically. As shown in Figure 2(d), vertical displacement was displaced by hydraulic jacks. The boundary of the legs is housed in a box-like frame that allows vertical movement but does not allow horizontal movement.

The allowable vertical base displacement was 5 mm, and the allowable horizontal base displacement was 7 mm, calculated from the formula for allowable base displacement. Tilt changes at base displacements of 10 and 15 mm were also observed.

2.3 Tilt change due to base displacement

The results of the test are shown in Figure 3. The top row of Figure 3 shows the results of vertical displacement, the middle row shows the results of horizontal displacement outside the tower, and the bottom row shows the results of horizontal displacement inside the tower. The vertical axis is the installation height of the tilt sensor, and the horizontal axis is the vector composite change in tilt angle. Unfortunately, leg d was the furthest away from the data logger, so some data was missing due to poor radio communication.

Figure 3 shows that when leg c is displaced vertically upward by 5 → 10 → 15 mm, the overall change in tilt angle at each measurement point becomes larger. Focusing on legs a, b, and c, the amount of change in tilt angle was greater at the top than at the bottom panel. During allowable vertical displacement, the three sensors installed on the same member at the lowest section differ in tilt change by a maximum of 0.02 deg. Also, leg c shows that the member is bent.

Next, the results for horizontal displacement are shown. As in the case of vertical displacement, the change in tilt angle increases with the increase in base displacement. However, the amount of change for main members other than leg c, which is subjected to forced displacement, is considerably smaller than that of leg c by approximately 30 % or less.

During allowable horizontal displacement, the three sensors installed on the same member of the lowest section show that the tilt change differs by a maximum of 0.04 deg. In particular, a large tilt change can be seen in the movable leg at the time of horizontal displacement outside the tower, even though it is the same component.

3 ANALYSIS MODEL AND RESULTS

The change in tilt of the lowest part due to base displacement be confirmed by analysis. The analytical model was created using ADINA (ver. 9.4). The analytical model created is shown in Figure 4 (a). The analytical model was made up of nodes at the member intersections and a beam element between the nodes. The analytical model was subjected to the same forced base displacements as in the test, and the member stresses, displacements of the member nodes, and member tilt were calculated and compared with the test results. The test tower

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has only one movable leg (leg c). When the leg c was displaced horizontally, the vertical displacement was fixed and rotations were free as the boundary condition. On the other hand, the boundary conditions were free for vertical displacement and rotation in all directions when the vertical displacement was given to leg c.

The tower used for the full-scale test did not have any electric cables. Therefore, an analytical model without the weight of the wires and tension loads was used in the analysis. Bolt slippage model [6] was considered in the analytical model. The steel tower consists of members joined by bolts. Since there is a bolt clearance of 1.5 to 2.0 mm, the bolts may slip when base displacement occurs. To account for the deflection of the main column members identified in the test results, the main column members were divided into the bottom to the fourth panel of horizontal members. In addition, a model was also created to account for the cross-sectional area of the overlapping joints of the main column members and the eccentricity of the joints of the main column members. Tilt changes were compared in these models.

The above analytical model was used to perform the analysis, and Figure 4 (b), (c) shows a comparison of the analytical and experimental results at the allowable base displacement. The vertical axis is the steel tower height, and the horizontal axis is the vector composite change in tilt angle. Figure 4(b) shows that the eccentric model has the smallest error of 0.001 degrees in the range of 1.5 m to 1.9 m from the lowest point of the analytical model. Figure 4(c) shows the comparison results for the horizontal displacement outside the tower. As with the vertical displacement, the eccentricity model had an error of 0.004 degrees at 1.5 m to 1.9 m from the lowest point. Both vertical and horizontal displacements showed a large change in tilt and sensitivity at the lowest point. This analytical model is a simplification of the actual structure. Therefore, the accuracy of the model should be improved by refining the model in accordance with the actual situation. In this model, it can be said that the experimental data can be almost explained by refining the model up to the joints of the main column members. However, the model was not able to represent changes in tilt near the bottom of the tower. This is due to the shape of the base of the tower. As shown in Figure 4(d), there are areas near the base of a transmission tower in actual operation where only the main member is present. This area is called the bottom main leg. In general, the bottom main leg of a transmission tower in actual operation is about 300 mm. In contrast, the bottom main leg of the test tower was conducted is indicated as 500 mm on the drawing. In addition, the test tower has no concrete base. Therefore, the boundary between the tower and the base is ambiguous, and the length of the bottom main leg is also ambiguous. From the above, the authors believe that the difference in tilt change near the ground is due to the effect of the bottom main leg. In addition, a comparison of the case in which the eccentricity of the main column joints and the cross-sectional characteristics of the main column joints were taken into account showed that the maximum difference in tilt change was only 0.004deg.

4 RETEST RESULT

4.1 Test overview

The results of previous tests and analyses reveal that the bottom tilt change is highly sensitive to the sensor location. Therefore, a full-scale test was conducted again to investigate the sensitivity of the tilt change of the lowest section. The target tower was the same as in the previous test (Figure 2). In this experiment, 10 tilt sensors were installed on the main member of the legs as shown in Figure 5. Note that all four legs were installed in almost the same manner. However, the measurement interval of the tilt sensors was changed to 20 seconds to obtain more detailed data.

The base displacement was targeted at the allowable base displacement of 5 mm vertically and 7 mm horizontally. As in the previous test, vertical displacement was performed with hydraulic jacks and horizontal displacement was performed with turnbuckles.

4.2 Test result

Figure 5 shows the change in tilt of all sensors at the allowable base displacement. The horizontal axis is the tilt change along the x-axis and the vertical axis is the tilt change along the y-axis. From left to right: vertical displacement, horizontal displacement outside the tower, and horizontal displacement inside the tower. Purple dots indicate leg a, green dots indicate leg b, blue dots indicate leg c, and yellow dots indicate leg d. The one square interval in the figure indicates 0.05deg, and the red circle indicates the threshold value. The leg c of Id3 has no data because the sensor has failed. Also, the Id10 of leg c has too large tilt changes (-0.109, 0.144) to display the dots on the figure when the horizontal displacement outside the tower is given. The dots are plotted in the hidden upper left corner of the figure. The findings from Figure 5 are summarized below. The threshold value was exceeded only in the leg c where the base displacement was given.

The leg a has a larger tilt change from the top to the bottom. The leg b has the same tilt change at all points, but there is a twisting movement to the right in the upper to lower tilt change. The leg c subjected to base displacement showed a greater tilt change toward the top. The direction of the tilt change at Id10 was inverted from that of the other sensors. The threshold value was exceeded at any point when the height was 130 cm or more from the ground (Id6 or more). The leg d has the same tilt change at all points, but there is a twisting movement to the left in the upper to lower tilt change.

Except for leg c, the tilt change was very small at all locations. The tilt change was greater toward the lower part of leg c. Tilt change exceeding the threshold was observed below 150 cm from the ground (Id5 or less). Except for leg c, the tilt change was the same at all locations. The amount of tilt change was larger than the horizontal displacement outside the tower and was about the same as the vertical displacement. In leg c, the tilt change was greater toward the bottom. In addition, the tilt change occurred in the opposite direction to the other legs. Tilt changes that exceeded the threshold were observed when the leg was less than 150 cm from the ground (Id5 or less).

From the above, the recommended location for the tilt sensor is in Id 5 and 6. In addition, only the base displacement leg exceeded the threshold when the allowable base displacement was loaded. Therefore, the leg that exceeds the threshold value

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may be considered the leg where base displacement occurred. The direction of base displacement is determined by the total tilt change of the four legs.

Vertical displacement: Total tilt change of the 4 legs > Maximum tilt change of 4 legs

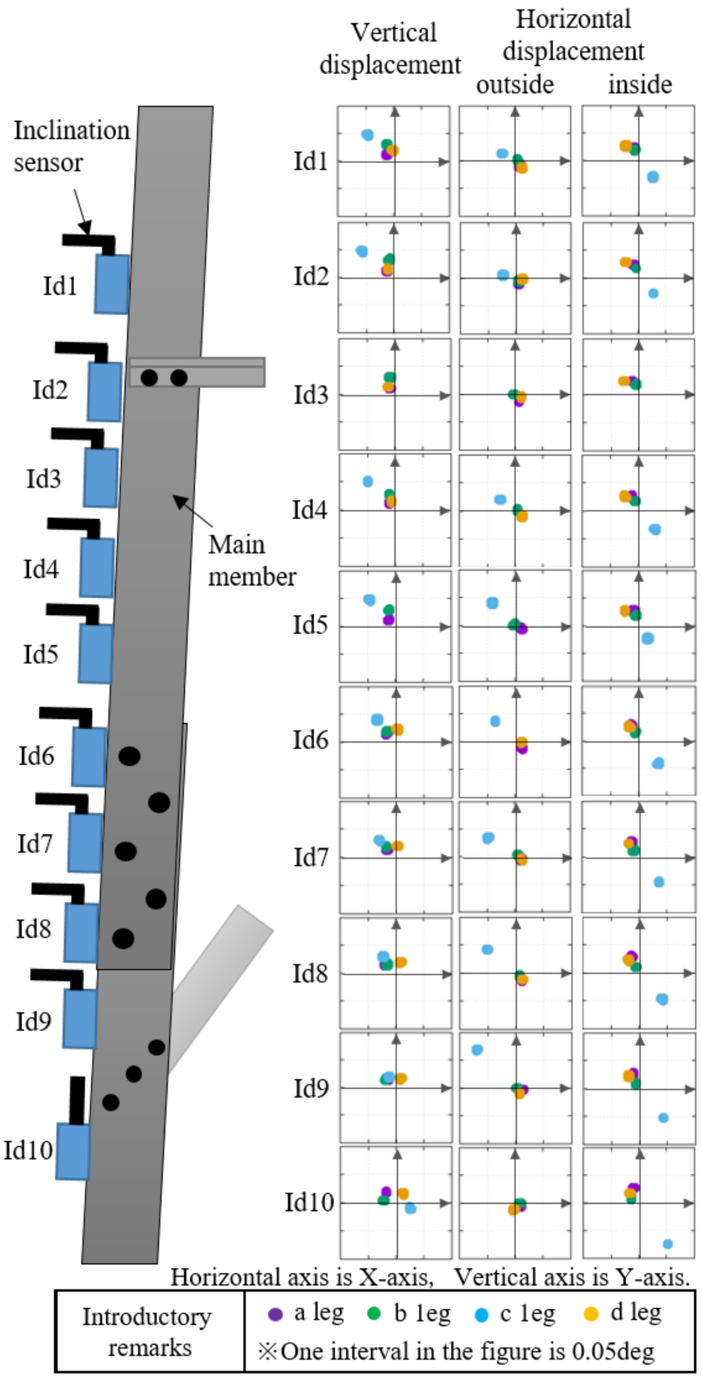

Figure 5. Test result

Horizontal displacement outside: Total tilt change of the 4 legs ≒ Maximum tilt change of 4 legs

Horizontal displacement inside: Total tilt change of 4 legs < Maximum tilt change of 4 legs

This test confirmed that the tilt change varies with base displacement, even for the same member. Therefore, care should be taken in the installation position when conducting actual monitoring.

It is easy to check the direction of inclination in more detail by checking the difference between ID2 and ID9. Vertical base displacement is larger for ID2 at the top when comparing ID2 and ID9. Horizontal base displacement is larger for ID9 near the ground when comparing ID2 and ID9. Thus, if several sensors can be installed, the direction of base displacement can be easily ascertained.

4.3 Re-comparison with analysis

The results of the analysis presented in Chapter 3 were compared with the results of the present measurement. The

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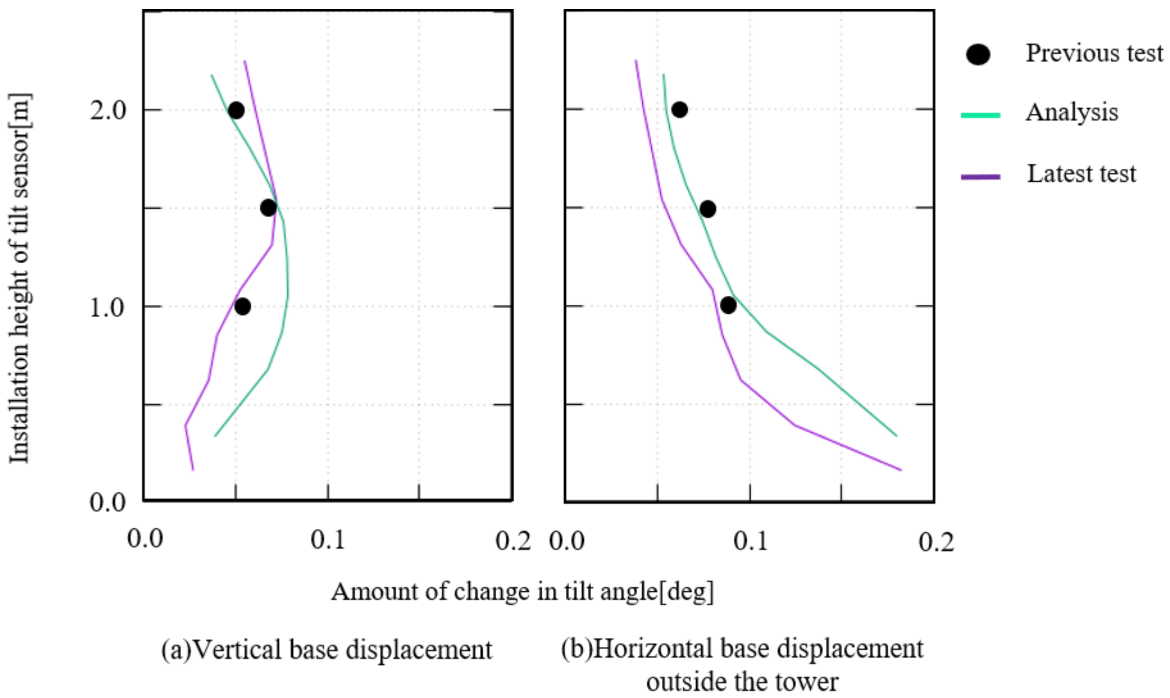

Figure 6. Re-comparison with analysis

results are shown in Figures 6(a) and 6(b). In Figures 6(a) and 6(b), the vertical axis is the steel tower height and the horizontal axis is the tilt change. The tilt change was assumed to be a vector in the line direction and in the direction orthogonal to the line. Figure 6(a) shows the comparison results of vertical base displacement and Figure 6(b) shows the comparison results of horizontal base displacement outside the tower. The black dots are the results of the previous test, the green line is the results of the analysis, and the purple line is the results of the latest test.

Figure 6(a) shows that the trend of tilt change was consistent with the previous test results. However, there was a difference of about 0.01deg at 2.0m. The retest was conducted two years later. Therefore, the authors consider it to be the effect of rust and other factors that were not present last time. Also, the last test was in October and the current test was in May. The difference in temperature may have affected the expansion of the materials. Compared to the analysis results, the overall trend was similar, but the height directions did not match. However, the locations between 1.4 m and 1.6 m were in general agreement with the analysis.

Figure 6(b) shows that the overall tilt change was smaller than the previous result, but the trend of tilt change was consistent. The trend was consistent with the analysis results. The factors contributing to the overall small change in tilt are considered to be the same as for the vertical displacement.

From the above, it was found that the trend of tilt change due to base displacement was generally consistent for the 1.4 to 1.6 m point.

5 CONCLUSION

As a result of the full-scale test, only the displacement leg had a large tilt change that exceeded the threshold value for vertical displacement. In the horizontal displacement, the tilt changes also exceeded the threshold value only for the displacement leg. This indicates that base displacement is most likely to occur at the leg with the greatest change in tilt. The recommended location is between 1.4 m and 1.6 m, which was in high agreement with the analytical calculations.

Horizontal displacement and vertical displacement can be determined by comprehensively checking the tilt changes of the four legs. The direction of base displacement can be determined by the sum of the tilt changes of the four legs as follows.

Vertical displacement: Total tilt change of the 4 legs > Maximum tilt change of 4 legs

Horizontal displacement outside: Total tilt change of the 4 legs ≒ Maximum tilt change of 4 legs

Horizontal displacement inside: Total tilt change of 4 legs < Maximum tilt change of 4 legs

If the direction of base displacement is to be determined in more detail, it is desirable to install the sensor near the base in addition to the recommended position of 1.4 m to 1.6 m. The reason for this is that the closer to the ground, the greater change in inclination can be observed due to horizontal displacement, so by checking the difference in inclination from the recommended position, the direction of base displacement can be determined more clearly.

The results of this test showed that by installing tilt sensors on the four legs at the recommended locations, it is possible to determine the leg where base displacement occurred and the direction of base displacement.

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