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Technical Paper

Deformation of the foundation and structure of Tomioka Silk Mill's East Cocoon Warehouse

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Abstract

The East Cocoon Warehouse of the Tomioka Silk Mill was constructed in Japan in the Meiji era using technology introduced from abroad. Deformation of its foundation stones and the building as a whole was measured as part of a civil heritage geotechnical study. The maximum differential settlement among the 92 foundation stones of the warehouse spanning a total wall length of 233.4 m was 44 mm. The distance between the foundation stones of the eastern and western walls was 12.5 m, and the maximum differential settlement among the four foundation stones along the southern and northern walls was 13 and 19 mm, respectively. The measurement results indicate that the inclinations of the pillars were not influenced by changes in the elevation of the foundation stones or the presence of gaps in the continuous stone rows. The difference between the maximum and minimum elevations in the silk reeling mill was 33 mm for the 71 foundation stones along the total 325-m wall length. These results illustrate that the level of geotechnology at the beginning of the Meiji era was similar to that of recent technology, and the East Cocoon Warehouse has remained in its original state and location, standing on its simply and suitably built foundation for 145 years.

Keywords: World Heritage Site; Settlement of foundation; Inclination of floor and foundation; Timber-framed brick construction

1. Introduction

Historical structures and remains are part of the heritage humankind hands down to posterity. As records, they describe not only the construction technologies of the past but also carry information about the social system and culture of their time. Many historical civil engineering structures constructed during and after the Edo era still remain in Japan. Some of these structures, such as the Yokosuka dry docks, played an important part in the fate of the nation, including the Japanese social system and cultural tradition (Shogaki, 2014). However, such artifacts have not been the subject of sufficient systematic geotechnical research or publicity. In 2011, the Kanto Branch of the Japanese Geotechnical Society (KBJGS) established an academic committee for the technical evaluation of historical structures constructed during and after the Edo era, and a symposium on the geotechnical evaluation of civil engineering heritage was held in 2014 after much research activity (KBJGS, 2014). An Asian Regional Technical Committee on Geoengineering for the conservation of heritage monuments and historical sites (ATC-19, 2014) has also been active in this field, together with the International Society on Soil Mechanics and Geotechnical Engineering (ISSMGE). However, standardization of methods for geotechnical analysis and evaluation of historical structures is still at an early stage. In 2015, an academic committee to examine the fundamental direction of further geotechnical

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Nomenclature

D_c	distance from southeastern corner (m)	f_r	cumulative relative frequency (%)
D_e	distance from eastern pillar (m)	G	width of gaps between continuous stones (mm)
D_r	distance from southeastern foundation stone (m)	I_f	inclination calculated from the unevenness of neighboring foundation stones (mm/m)
D_s	distance from southern wall (m)	I_p	inclination of pillar (mm/m)
E	elevation (m)	N	standard penetration test (SPT) blow number

study of historical structures was formed within the KBJGS.

The following is a list of major research topics and goals related to the study of historical structures reported by the KBJGS academic committee (KBJGS, 2014).

(1) Accumulation of geotechnical information on historical structures.
(2) Study of the technical history of geotechnical fields and chronological changes in historical structures.
(3) Damage assessment, preservation, and restoration of historical structures.
(4) Contributions to future designation of historical structures as national treasures and world heritage properties.
(5) Cooperation with Western geotechnical societies in studies of historical structures with a focus on new technologies that were imported from the West during the modernization of Japan.

The Tomioka Silk Mill was constructed in 1872 using technology introduced from France. Most of the buildings have been preserved, and the mill was registered as a World Heritage Site under the designation “Tomioka Silk Mill and Related Sites” on June 24, 2014. In addition, the East and West Cocoon Warehouses and the silk reeling mill were also registered as national treasures on December 10, 2014. These buildings employ truss structures and a timber-framed brick construction. They were designed by Edmond Auguste Bastien, who was assigned to the Yokosuka Iron Works. These buildings are 145 years old and have been restored in their entirety by Tomioka City. Shogaki et al. (2015) investigated the inclination of the pillars and the sinking of the foundation and floors in the West Cocoon Warehouse of the Tomioka Silk Mill and found those in the northern part of the warehouse to be larger than those in the southern part as a result of the consolidation settlement of the underlying clayey soil. The maximum differential settlement among the 92 foundation stones of the West Cocoon Warehouse spanning a total wall length of 233.4 m was found to be 43 mm. The distance between the foundation stones of the eastern and western walls was 12.5 m, and the maximum differential settlement among four measured foundation stones in the southern and northern walls was found to be 12 and 17 mm, respectively. However, if the study by Shogaki et al. (2015) had been conducted with the aim of applying the findings to the conservation and repair of specific wooden structures, it would have been necessary for them to consider the preservation and restoration of the structures and to establish technical regulation criteria regarding the effects of the pillar inclination and foundation stone settlement on the stability of the structures. Their study was not conducted with such aims in mind, and no such criteria exist.

Laefer (2008) has described the performance expectations of early 20th-century urban American building foundations in terms of foundation reuse based on an investigation of four types of foundation materials typical of early 20th-century construction: corbelled brick, ashlars, corbelled brick with continuous concrete slab, and uncemented paving stones. Street and Clark (1896) reported the ASCE 1887-88 pier test data as the original composite strength of masonry for the historical ashlars foundation. However, these types are different from the timber-framed brick construction of the Tomioka Silk Mill, which has wooden pillars and bricks on the foundation stones. Additionally, no previous geotechnical studies have been conducted on other similar historical wooden structures, not even on structures outside Japan. Therefore, the present study represents the first geotechnical study on the foundation of a historical wooden structure, and as such, the results and considerations obtained herein will provide a basis for the future development of preservation and restoration processes, providing a first step toward the determination of technical preservation and restoration criteria.

In this study, the deformation of the foundation stones and the building of the East Cocoon Warehouse of the Tomioka Silk Mill, which was constructed using technology introduced from abroad, was measured and discussed in comparison with that of the West Cocoon Warehouse (Shogaki et al., 2015). This work is part of a geotechnical study of Japan’s civil engineering heritage, as described by the five foci listed above; an earlier part of this geotechnical study focused on the deformation of the foundation and structure of the Shirakabe barracks of the 16th infantry regiment (Shogaki and Nakagawara, 2016). The level of geotechnical engineering at the beginning of the Meiji period is also theorized.

2. Overview of the ground and foundation structures of the East Cocoon Warehouse

Photograph 1 shows a perspective view of the Tomioka Silk Mill. The Kabura River flows along the southern side of the property. The silk reeling mill is located at the southern end of the complex. The major axes of the East and West Cocoon Warehouses run north–south. The Tomioka Silk Mill is located on a terrace by the Kabura River at an elevation of approximately 167 m. An elevation view of the southern side of the East Cocoon Warehouse is shown in Fig. 1 (Tomioka City Board of Education, 2006). The building is 14.01 m wide, 14.80 m high, and 107.71 m long. It has a total of 92 pillars; 30 each are located along the eastern and western walls, 28 are in the center, and two each are located along the northern and southern walls. Cedar pillars approximately 10 m long support the second floor and the roof. These features are similar to those of the West Cocoon Warehouse (Shogaki et al., 2015).

Fig. 2 shows a plan view of the pillars of the West Cocoon Warehouse. The plan view of the Tomioka Silk Mill and the locations of five borehole sites B-1 to B-5 around the mill complex are shown in Fig. 3, and a cross-sectional soil profile obtained from these boring samples is shown in Fig. 4. A loam layer that varies in thickness from 0 to 50 cm was present in the upper layer of the terrace deposits. However, a clay layer was only present around B-1. The reclaimed soil at the five dynamic cone penetration test sites D-1 to D-5 (Fig. 2) can then be deemed to include the loam but not the clay, which was observed only at B-1.

Photograph 1. Perspective view of the Tomioka Silk Mill. Reproduced from Tomioka City, 2013.

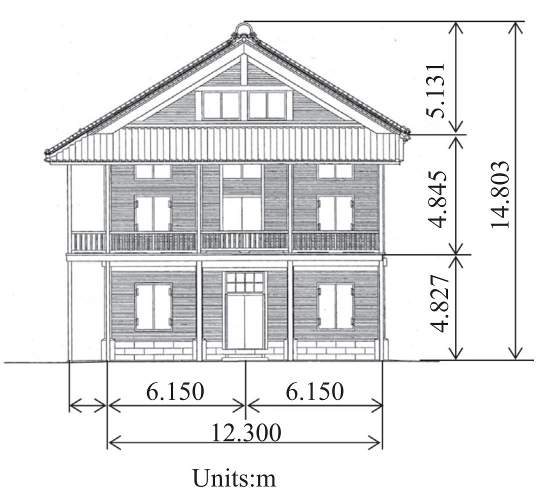

Fig. 1. Elevation view of the southern face of the East Cocoon Warehouse. Reproduced from Tomioka City, 2006.

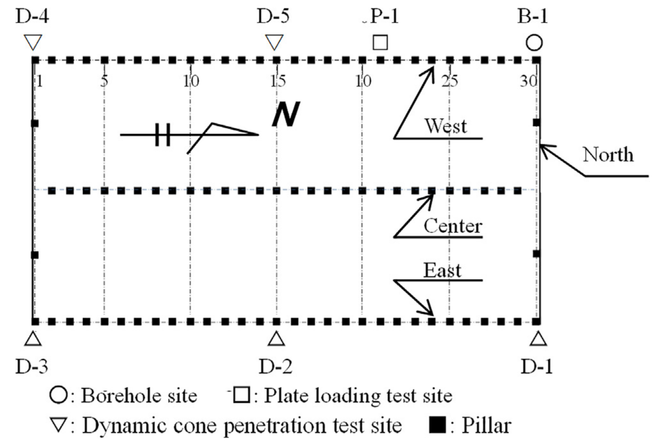

Fig. 2. Layout of pillars in the West Cocoon Warehouse.

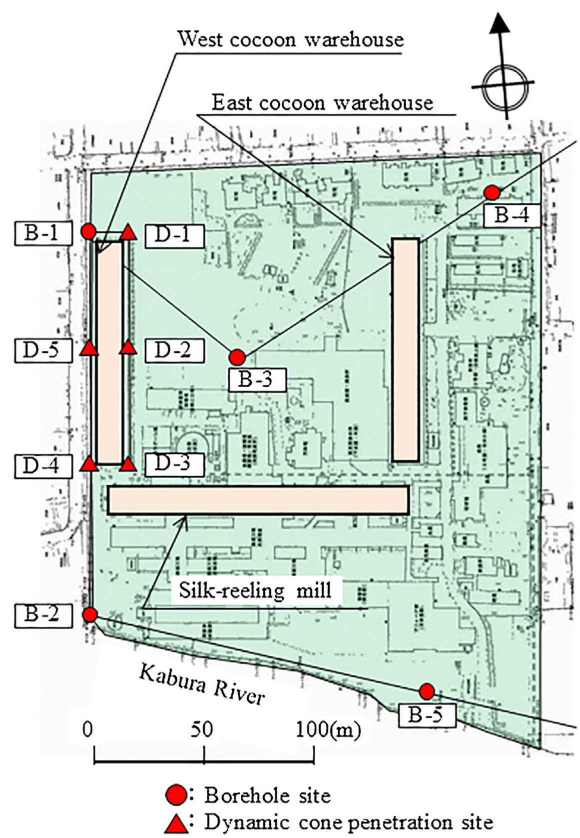

Fig. 3. Plan view of the Tomioka Silk Mill and borehole sites. Adapted from JACAM, 2011.

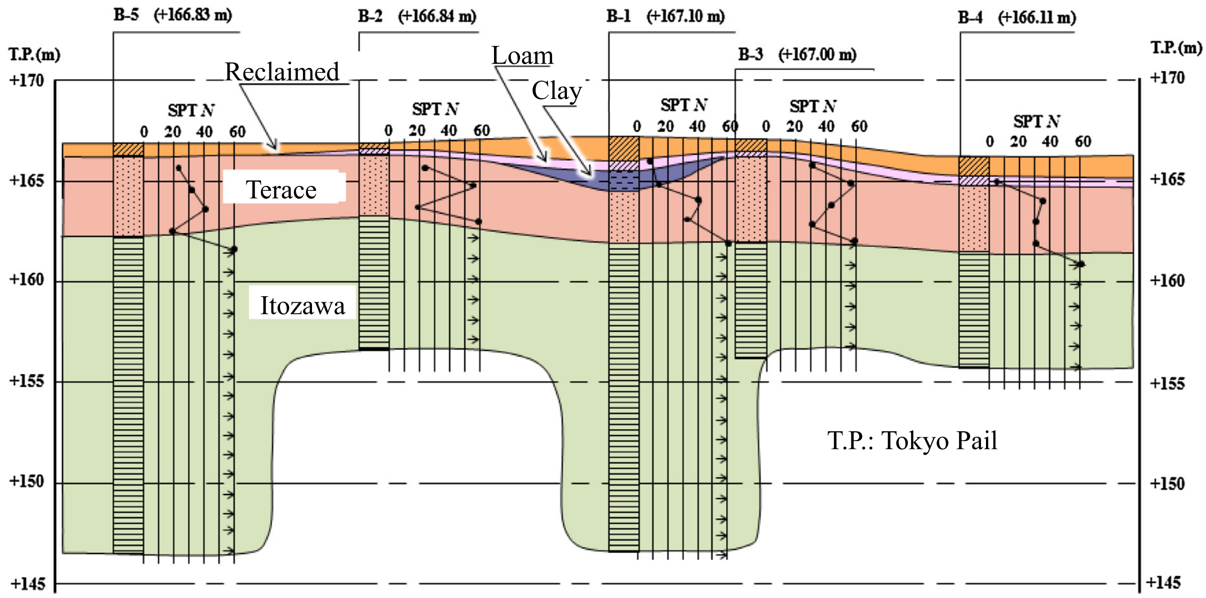

Fig. 4. Cross-sectional soil profile obtained from boring samples. Reproduced from JACAM, 2011.

Photograph 2. Foundation and continuous stones.

Photograph 3. Foundation structures. Reproduced from Tomioka City, 2013.

The loam, clay, and terrace deposit strata under the reclaimed soil are Pleistocene deposits. The natural water content, liquid limit, and plasticity index of the Pleistocene clay are 40%, 56%, and 30%, respectively, and the fraction of grains larger than 0.075 μm is 14%, as reported by the Japanese Association for Conservation of Architectural Monuments (JACAM, 2011). The reclaimed soil and loam layers at the borehole locations B-1 to B-4 were 1.8 and 0.6 m thick, respectively. The N_d values for the portable dynamic cone penetration test Japanese Geotechnical Society (2000) at these locations ranged from 2 to 10 (JACAM, 2011). JACAM (2011) have reported that the ultimate bearing capacity obtained from a plate loading test at P-1 is 226.3 kN/m^2. This is a conservative estimate, as the embedded depth was not taken into consideration. The presence of a clay layer was not confirmed at the site of the East Cocoon Warehouses; however, the clay layer can be considered to have sufficient bearing capacity for the weight of the stored cocoons and the timber-framed brick construction (approximately 81 kN/m^2). The ratio of the ultimate bearing capacity (226.3 kN/m^2) to the weight (81 kN/m^2) of the stored cocoons and the timber-framed brick construction is 2.8. This ratio is considered as the safety factor for similar current construction method. The northern half of the West Cocoon Warehouse was used for coal storage for the first 24 years of the building's life. The first floor of the building was constructed in 1896 (Tomioka, 2013), and concrete was placed in the spaces between the foundation stones in 1981, as shown in Photograph 2.

Photograph 3 shows the foundation and brick wall. Two stones with a diameter of approximately 50 cm were placed

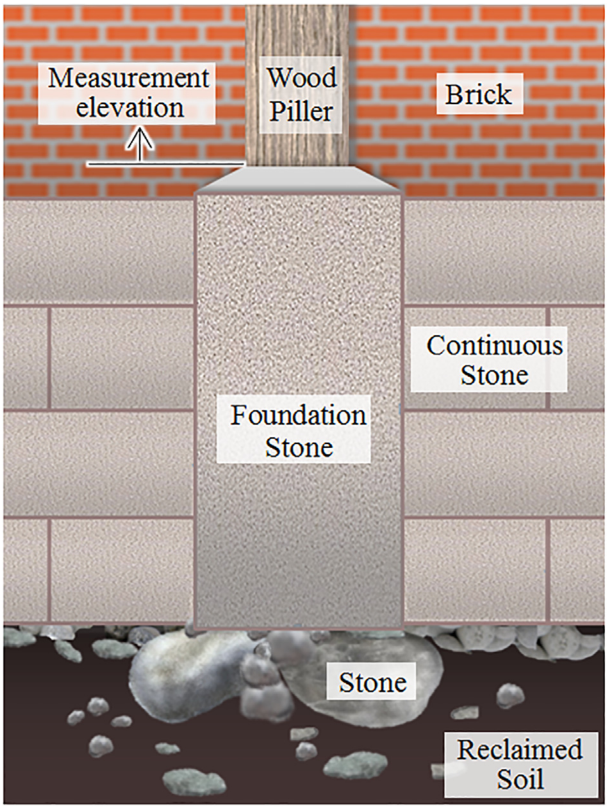

Fig. 5. Schematic diagram of the foundation based on Photograph 3.

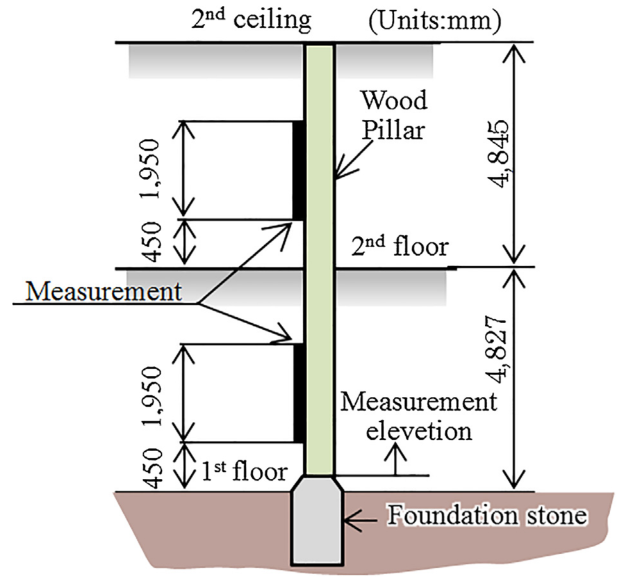

Fig. 6. Measurement section for the pillar inclinations and the elevation of foundation stones.

between the pillar foundation and the reclaimed soil, and a 30-cm-deep layer of stones with a diameter of approximately 10 cm was placed on the reclaimed soil under the continuous rows of stone walls, as shown in Fig. 5. These comprise a simple structural foundation system. During construction, foundation stones were carried from Mt. Renseki, which is near the Tomioka Silk Mill and in the present-day town of Kanra (Tomioka City Board for Education, 2006). The type of stone that was used for these foundation stones has been called Tago-stone. Geologically, these stones are from the Miocene Ushibuse Formation, which is mainly composed of yellowish brown arkosic coarse sandstone (Tanaka et al., 2013). The sandstone has a particle density of 2.2 g/cm^3, a porosity of 13.6%, and an unconfined compression strength of 28 MN/m^2 (Okubo et al., 2000). Such physical and mechanical properties were not directly measured from the foundation stone in the Tomioka Silk Mill. In the case of ordinary concrete, the required structure design strength is 24 MN/m^2 for medium- and low-rise buildings, as reported by the Ministry of Land, Infrastructure, Transport and Tourism (MLITT, 2018). Tago-stone may have sufficient strength to support the weight of the timber-framed brick building of the East Cocoon Warehouse. On the basis of this information, the system appears to have been installed after careful consideration of the strength of the terrace deposits and the low weight of the building.

3. Procedure for measuring pillar inclination and foundation stone settlement

MLITT is in charge of issuing technical guidelines for settling housing disputes in Japan. The guidelines identify

Table 1
Statistics for pillar inclination.

Floor	Wall	Side	Number of pillars n	Mean inclination (mm/m)	Standard deviation
First	Eastern	Northern	1	−2.5	–
		Southern	11	1.9	2.4
	Central	Northern	14	1.7	2.9
		Southern	14	−0.9	4.9
	Western	Northern	15	−1.0	6.1
		Southern	13	−5.1	2.8
Second	Eastern	Northern	15	−0.6	5.7
		Southern	15	4.1	4.1
	Central	Northern	14	−0.7	4.8
		Southern	14	3.8	3.1
	Western	Northern	15	2.2	4.3
		Southern	15	−1.1	3.0

Photograph 4. Gap between continuous stones measured using a vernier caliper.

three levels for the inclination of floors and pillars in residential construction based on the amount of inclination per unit length of the measurement target (MLITT, 2002): Levels 1, 2, and 3 are less than 3 mm/m, 3 to 6 mm/m, and more than 6 mm/m, respectively. Table 1 summarizes these levels. The floor should not incline more than 9 mm per 3 m of length in level 1 and should be more than 3 m long for all of the levels. To measure the inclination I_p of a pillar, the pillar should be more than 2 m long (MLITT, 2002). In this study, I_p was obtained based on measurements of the pillar at heights of 45 and 195 cm above the floor surface, as shown in Fig. 6, yielding a total pillar test section length of 1.5 m. The measurement precision of the inclinometer was 0.1 mm, and the measured values for the test section lengths of 1.5 m were converted to 1 m equivalents by multiplying by 66.7% (=2/3). Hereafter, the inclinations are reported in units of millimeters per meter of pillar length based on these 1 m equivalents. The sinking of the foundation stones was measured using a total station (TS). The I_p values were obtained from measurements taken on the eastern face for the western and central pillars and the western face for the eastern pillars. The East Cocoon Warehouse was used for cocoon storage. The criteria were used as reference values because no specific criteria exist for storehouse structures.

The foundation stones are Miocene sandstone with a height of 1 m and square cross sections with 60 cm sides. Approximately 60 cm of the height of the stones is exposed at the East Cocoon Warehouse, as shown in Photograph 2. The elevation E of the tops of the foundation stones was measured using the TS, which has a precision of 1 mm for distance measurements and 5″ for rotation measurements. Continuous rows of stones are present between the foundation stones. These rows are 90 cm long and 30 cm high and are composed of the same stone material as the foundation stones. There is no connecting material between the continuous stones, and they are in direct contact with each other. The width G of each of the gaps between the continuous stones was measured to within 0.01 mm using a vernier caliper, as shown in Photograph 4. The inclination of the pillars and the settlement of the foundation stones were measured in December 2014, and the gap widths G were measured in February 2015. The elevations of the foundation stones on the western side of the East Cocoon Warehouse could not be measured because the adjoining Cocoon Drying Facility had fallen down as a result of a snowstorm in 2015. Therefore, the elevations of the foundation stones on the East Cocoon Warehouse were newly measured in March 2017. However, except for those on the western side of the East Cocoon Warehouse, the elevations of the foundation stones obtained in March 2017 were similar to those in February 2015.

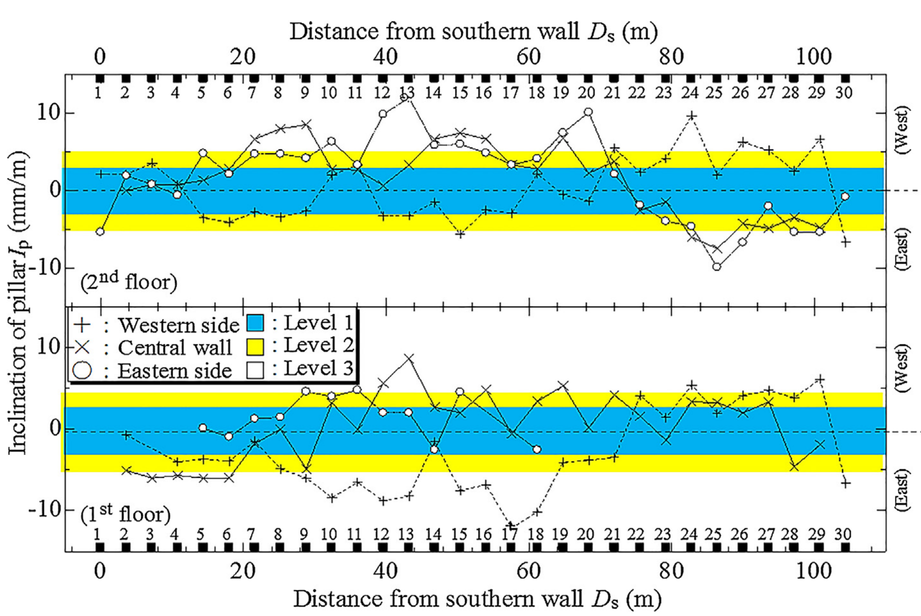

Fig. 7. Inclination of measured pillars plotted against distance from southern wall.

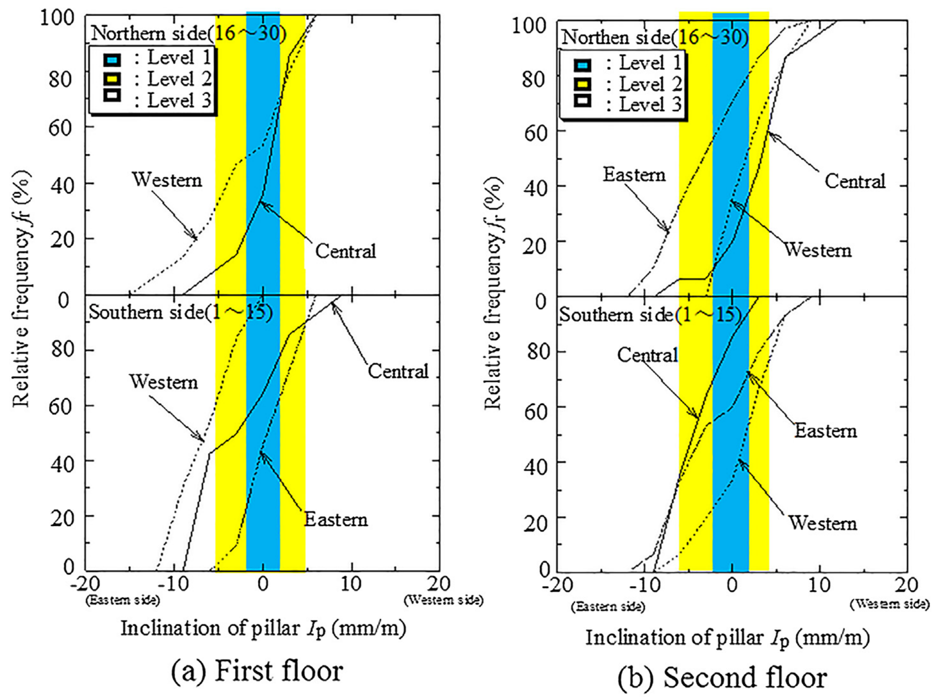

Fig. 8. Cumulative relative frequency distribution of I_p. (a) First floor. (b) Second floor.

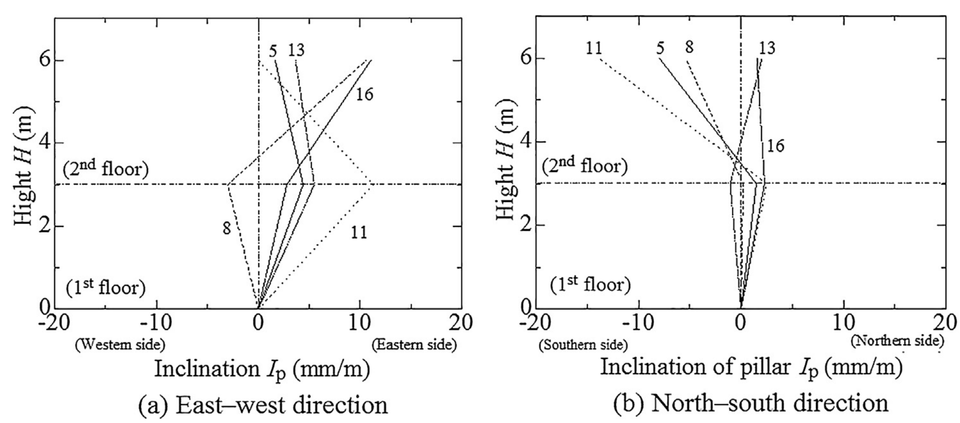

Fig. 9. I_p and direction of inclination for representative pillars (central pillars). (a) North–south direction. (b) East–west direction.

4. Pillar inclinations

The east–west inclinations obtained for the western, central, and eastern pillars of the first and second floors are plotted against the northward distance D_s from the southern wall in Fig. 7. Positive and negative I_p values indicate inclination to the west and east, respectively. Fig. 7 also shows the three level criteria given as colored bands. The number of measured pillars was 68 and 88 of the 92 pillars for the first and second floors, respectively; the I_p values of the pillars on the northern half of the first floor could not be measured, because this area is used as the Tomioka Silk Exhibition Hall.

There are many pillars with I_p values that fall within the level 2 or 3 inclination limits. Such pillars are present in various locations throughout the structure. Therefore, the East Cocoon Warehouse would likely be rated as having a defect level of 2, with the possibility of a level 3 rating for structural resistance, if it were being considered under the housing regulations.

The characteristics of the I_p values are summarized as follows:

(1) The southern pillars (pillars 1–21 in Fig. 2) along the western wall on the first floor are inclined toward the east. However, the inclination of the northern pillars (pillars 22–30) along this wall is westward and increases gradually with increasing distance from the southern wall. This tendency is similar to that for the pillars along the western wall on the second floor.

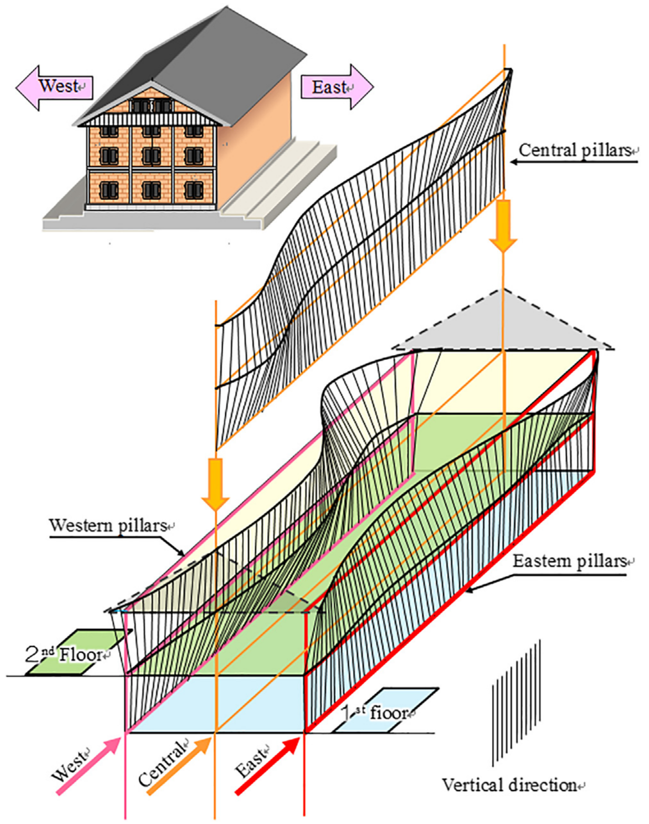

Fig. 10. Overall schematic of pillar deformation in the East Cocoon Warehouse.

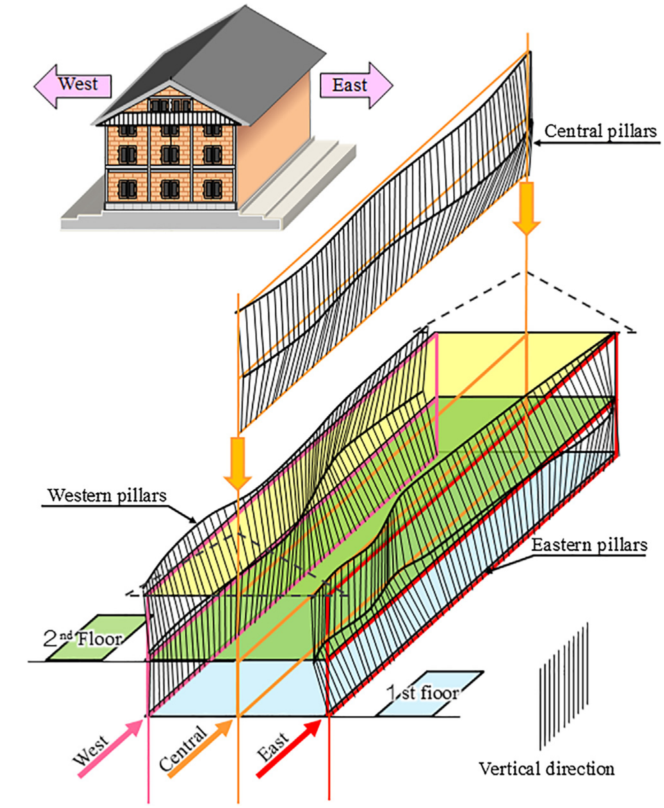

Fig. 11. Overall schematic of pillar deformation in the West Cocoon Warehouse. Reproduced from Shogaki et al., 2015.

(2) The southern pillars (pillars 1–18) along the eastern wall on both the first and second floors are slightly inclined toward the west. However, the northern pillars (pillars 22–30) along the eastern and central walls on the second floor are inclined toward the east. In combination with the westward inclination of the pillars along the western wall, this eastward inclination of the eastern and central pillars indicates the twisting of the building.

Because the tendencies of the I_p values for the pillars on the northern and southern sides of the building are different, the cumulative relative distribution of the east–west inclination for the first and second floors is shown in Fig. 8(a) and (b), respectively, with the northern (pillars 1–15) and southern (pillars 16–30) pillars shown in separate plots, and the corresponding statistical measures are given in Table 1. The cumulative relative frequency f_r of a given value of I_p^* is defined as the ratio of the number of measured pillars with $I_p \leq I_p^*$ to the total number of measured pillars. All of the southern pillars (pillars 1–15) along the western wall on the first floor are inclined toward the east, and approximately 50% of the northern pillars (pillars 16–30) along this wall are inclined toward the west, as shown in Fig. 8(a). As shown in Fig. 8(b), the central pillars on the first floor are inclined toward the east, regardless of their location along the north–south direction.

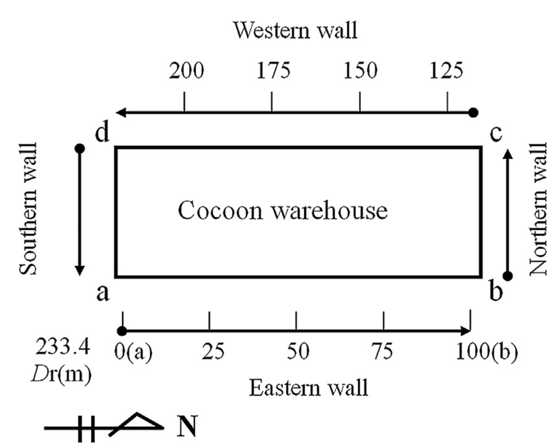

Fig. 12. Definition of D_r.

The inclinations in the east–west and north–south directions for central pillars 5, 8, 11, 13, and 16 in Fig. 2 are shown in Fig. 9(a) and (b), respectively. These pillars were selected as representative of the building as a whole, and no silkworm materials were near them, making measurement a practical task. It was assumed that the measured pillars maintain the same inclination within each floor. The maximum I_p magnitudes in the north–south and east–west

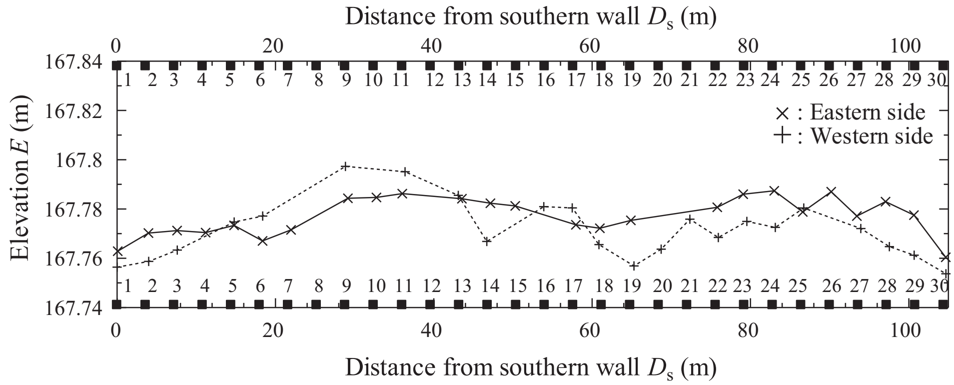

Fig. 13. Elevation of foundation stones on the western and eastern sides plotted against distance from the southern wall.

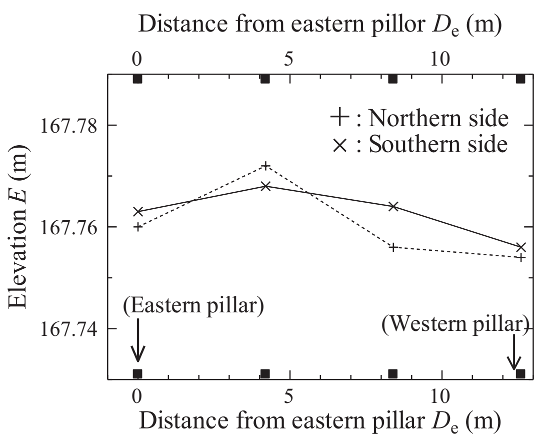

Fig. 14. Elevation of foundation stones on the northern and southern sides plotted against distance from the southern wall.

directions are 14 mm/m southward for pillar 11 (Fig. 9(b)) and 11 mm/m eastward for pillar 11 (Fig. 9(a)), respectively.

The deformation of all of the measured pillars in the building is schematically shown in Fig. 10. This figure allows qualitative visualization of the twisting of the whole building, as quantitatively described in Figs. 7–9. The deformation of the pillars in the West Cocoon Warehouse is shown in the same manner in Fig. 11 (Shogaki et al., 2015). This figure also shows the twisting of the building.

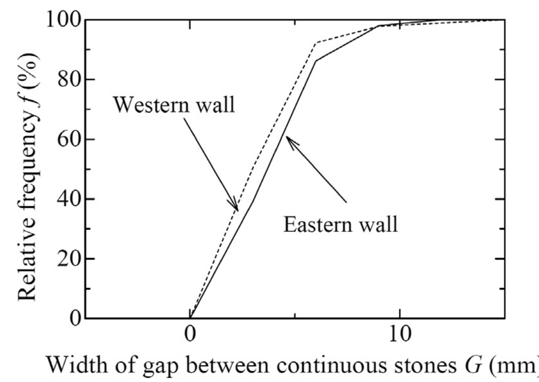

Fig. 16. Cumulative relative distributions of C including $C = 0$ mm along the eastern and western walls.

To counteract deformation in the east–west direction, the pillars inclined to the north–south direction, as shown in Figs. 10 and 11.

5. Relationship between foundation stone elevation and gaps in the continuous stone rows

Fig. 12 shows the definition of the distance from the southeastern foundation stone D_r around the warehouse. This distance is measured by following the path indicated by the arrows in Fig. 12 starting from the southeastern foundation stone, which is identified in the figure as (a).

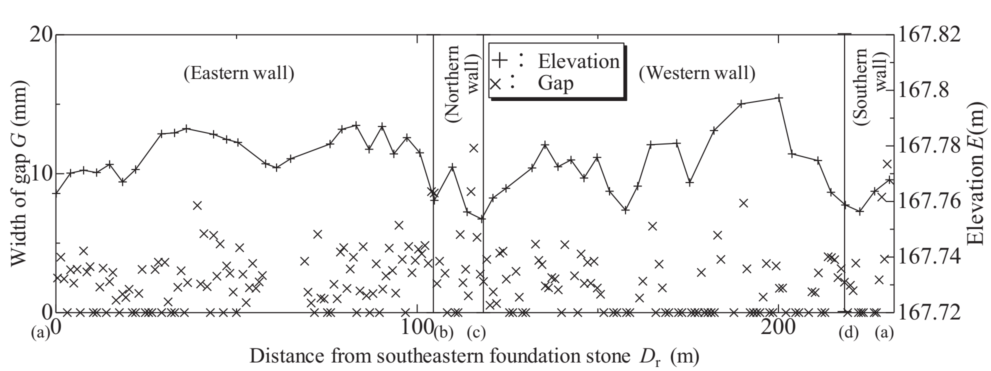

Fig. 15. Gap width and foundation stone elevation plotted against D_r.

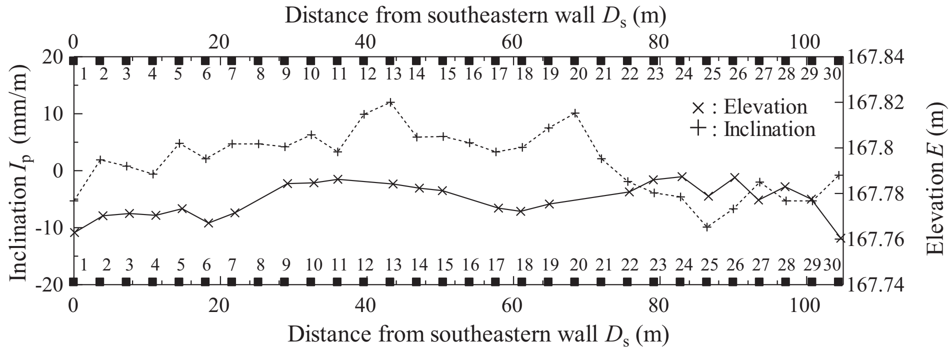

Fig. 17. I_p and E plotted against D_s for the eastern wall.

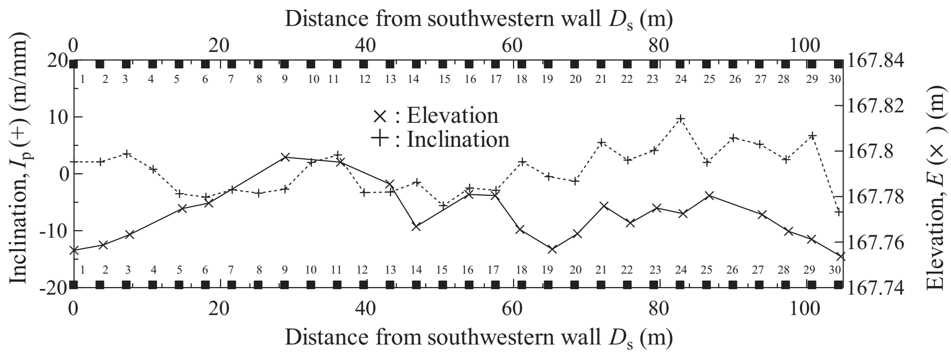

Fig. 18. I_p and E plotted against D_s for the western wall.

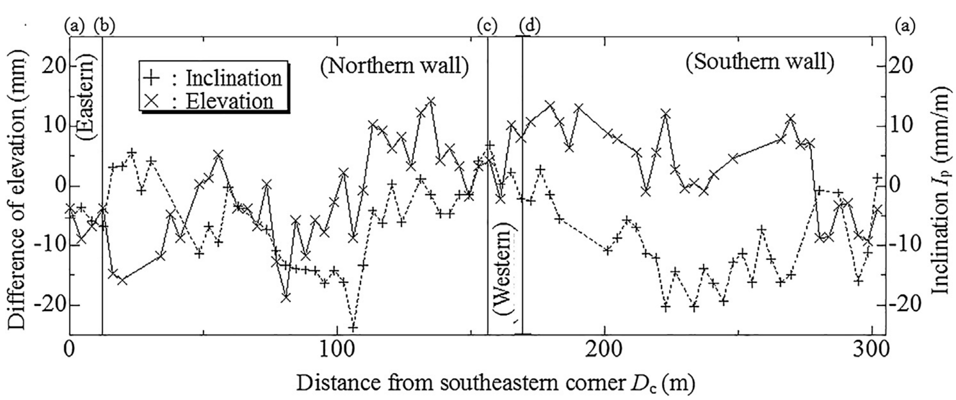

Fig. 19. I_p and E plotted against D_s for the silk reeling mill. Reproduced from Shogaki et al., 2015.

The total length around the warehouse is 233.4 m. Along this circuit, there are 64 foundation stones and 178 open gaps in the continuous stone rows. The elevation E of the foundation stones is plotted against D_s in Fig. 13. The foundation stone on the western side that supports pillar 8 located 26.8 m from the southern wall has the greatest elevation. The elevations on the western and eastern sides range from 167.754 to 167.797 m and from 167.760 to 167.787 m, respectively. The maximum difference in elevation over the total distance around the warehouse of $D_f = 233.4$ m is 44 mm. The mean elevations for the eastern and western sides are 167.777 m and 167.772 m, respectively. The elevation E of the pillars along the northern and southern walls are plotted against the distance D_e from the eastern pillar in Fig. 14. These pillars span a distance of 12.5 m along each wall. The pillars along the northern and southern walls are lowest on the western side of the building. The maximum difference in elevation for the northern and southern walls is 19 and 13 mm, respectively. These differences are similar to those for the West Cocoon Warehouse (Shogaki et al. 2015).

In Fig. 15, the gap width G and elevation E are plotted against D_r, as defined in Fig. 12, and the labels (a)–(d) along the horizontal axis correspond to the positions of the corners labeled in the same manner in Fig. 12. Incidents of no gap opening ($G = 0$ mm) are concentrated on the

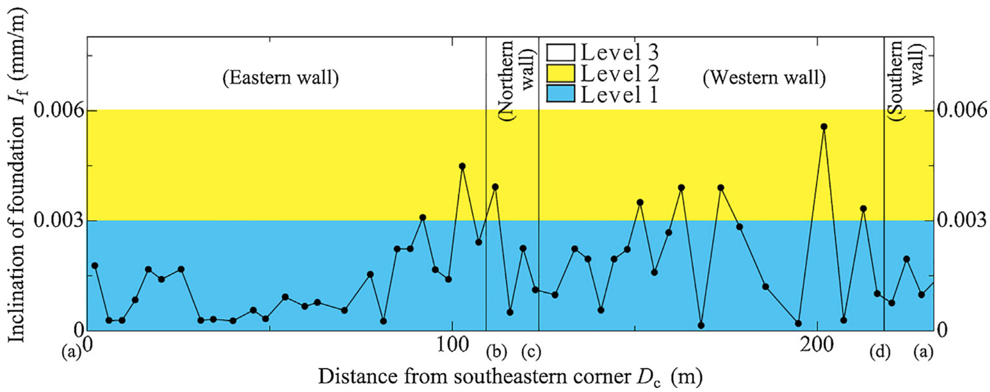

Fig. 20. I_f plotted against distance from the southeastern corner.

foundation stone side. Therefore, a nonzero G is caused by the horizontal deformation of the continuous stones between the foundation stones. The maximum G value for the eastern wall is 8.0 mm at a location of $D_c = 39$ m, and G is roughly constant at an average of approximately 3 mm on the eastern and western walls. On the northern and southern walls, the maximum G values are 12.5 and 11.4 mm, respectively, which are greater than those for the eastern and western walls, and they are unrelated to the E values, as shown in Fig. 15. Therefore, it can be considered from Fig. 15 that the continuous stones have foundation structures, as shown in Photograph 3, which suppress their vertical deformation. The cumulative relative distributions for the G values, including $G = 0$ mm, for the eastern and western walls are shown in Fig. 16. Fig. 16 allows a visual comparison of the mean values of G for the two walls and illustrates its standard deviation. The gap width G is in the range of 0–12.5 mm and is unrelated to whether the stones are on the eastern or western walls. The mean gap width $\bar{G}$ for the eastern and western walls are 2.3 and 1.8 mm, respectively, and are similar to those for the West Cocoon Warehouse (Shogaki et al., 2015).

6. Relationship between pillar inclination and foundation stone elevation

The pillar inclinations I_p on the second floor and the foundation stone elevations E are plotted against D_s for the eastern and western walls in Figs. 17 and 18, respectively. As stated in Section 4, the inclination of the pillars along the eastern wall on the first floor in the northern half of the East Cocoon Warehouse could not be measured because it is used as the Tomioka Silk Exhibition Hall. Therefore, only the I_p values for the second-floor pillars are plotted. These plots indicate that the pillar inclination is not influenced by changes in the elevation of the foundation stones. The I_p values obtained from the outside surface of the first-floor pillars in the silk reeling mill and the differences in the elevation of its foundation stones are plotted against D_c in Fig. 19 (Shogaki et al., 2015), where the mean value of E is normalized to 0 mm because the absolute elevation of the foundation stones of the silk reeling mill could not be measured. The I_p values in the silk reeling mill were also found to be unrelated to E and D_c, and the difference between the maximum and minimum elevations is 33 mm for the 71 foundation stones along the total 325 m wall length.

7. Discussion

The Tomioka Silk Mill, which includes the East Cocoon Warehouse, has been preserved since its construction in 1872. The pillars were found to show some inclination, as indicated in Figs. 7–11; 38% of the pillars are in Level 1, 39% in Level 2, and 23% in Level 3, according to the MLITT (2002). Unfortunately, it is not possible to obtain the initial inclination at the time of construction. However, 77% of the pillars have been kept in less than Level 2 inclination. The building was constructed on a terrace, and the terrace foundation is sufficiently strong to support the weight of the building, as shown in Fig. 4. The maximum difference between the elevations of the foundation stones due to settling is less than 44 mm over a distance of approximately 233 m, as shown in Fig. 13. Fig. 20 shows the inclination I_f calculated from the unevenness of neighboring foundation stones in the elevation from the result of Fig. 13. As shown in the figure, 85% of the I_f is in Level 1 and 15% in Level 2, and there is no Level 3 for the I_f. The measurements performed in this study indicate that it likely has not suffered much deformation since the establishment of The Tomioka Silk Mill, 145 years ago. Therefore, the degree of stability achieved by the East Cocoon Warehouse is similar to that required for modern-day buildings. It indicates that the level of geotechnology at the beginning of the Meiji era was similar to that currently available. In addition, the East and West Cocoon Warehouses and the silk reeling mill (Shogaki et al., 2015) have remained in their original state and location for 145 years, standing on their simple structural foundation system as shown in Photographs 2 and 3.

8. Conclusions

The conclusions obtained in this study can be summarized as follows. The maximum differential settlement among the 92 foundation stones of the East Cocoon Warehouse of the Tomioka Silk Mill, which spans a length of 233.4 m, was 44 mm. The distance between the foundation stones of the eastern and western walls was 12.5 m, and the maximum differential settlement among the four foundation stones along the southern and northern walls was 11 and 19 mm, respectively. The present measurement results indicate that the inclination of the pillars in the warehouse was not influenced by the change in the elevation of the foundation stones or the presence of gaps in the continuous stone rows. The difference between the maximum and minimum elevations in the silk reeling mill was 33 mm for the 71 foundation stones along the total 325 m wall length.

These results illustrate that the level of geotechnology at the beginning of the Meiji era was similar to that of recent technology, and the East and West Cocoon Warehouses and the silk reeling mill (Shogaki et al., 2015) have remained in their original state and location, standing on their simple structural foundation system, for 145 years.

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