Case Study

Performance Assessment Using Structural Analysis and Spatial Measurement of a Damaged Suspension Bridge: Case Study of Twantay Bridge, Myanmar

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Abstract: A performance assessment of the Twantay Bridge, Myanmar, which is a suspension bridge that has been damaged by the movement of anchorages due to the soft soil conditions, was conducted based on simple monitoring, spatial measurements by three-dimensional (3D) terrestrial laser scan, and structural analysis with the finite-element method (FEM). Simple monitoring can capture the present progress of main-tower inclinations. This study proposes a method for capturing the overall deformation of bridges based on spatial measurement by 3D terrestrial laser scan. The FEM analysis was able to appropriately reproduce the deformation history of the suspension bridge after the construction, which was caused by movement of the anchorage blocks. Thus, the deformation of the main towers obtained with FEM was found to almost agree with that measured by the 3D terrestrial laser scan. In addition, by giving external loads, ultimate capacities were evaluated. This study clarified that a combination of simple monitoring, spatial measurements by 3D terrestrial laser scan, and structural analyses by FEM is useful for the safety assessment of and maintenance strategy for damaged suspension bridges. **DOI: 10.1061/(ASCE)BE.1943-5592.0001293.** *© 2018 American Society of Civil Engineers.*

Introduction

At present, many developing countries are in a period of rapid construction of infrastructures, especially in the Asian region. Most of the developing countries need support from other countries because advanced skills and technologies are required for appropriate design, construction, and maintenance of infrastructures. The Republic of the Union of Myanmar (hereinafter referred to as Myanmar) is a country located in Southeast Asia. Myanmar is one of the countries in which the construction of infrastructures is expected to increase dramatically in the near future. In Myanmar, design and construction of infrastructures are mainly conducted by the Ministry of Construction (MOC), and one of the problems is that construction records are insufficient. In recent years, problems with infrastructures due to soft ground conditions have been reported (JIP 2012), especially in the urban region of Yangon, which is the biggest city in Myanmar. The Twantay Bridge, a suspension bridge located on the southwest side of Yangon, is one example of such problems. It is reported that after this bridge was constructed, the main towers were inclined toward the main span, and the camber was decreased by approximately 500 mm in the maximum because of the movement of the anchorages. For bridges having such problems, not only a safety assessment of the present state but also countermeasures for maintenance in the future are required; however, if the construction record is not available, it is difficult to consider countermeasures from only the present condition. The Kutai Kartanegara Bridge is a suspension bridge in Indonesia that experienced incline of the main towers and decreased camber similar to the present state of the Twantay Bridge. During the restoration work of the Kutai Kartanegara Bridge, a clamp pin connecting the hanger cable to the main cable ruptured, and the bridge collapsed. Kawai et al. (2014) investigated the possibility of brittle failure of the clamp pin based on the results of the Charpy impact test and concluded that the collapse of the Kutai Kartanegara Bridge was due to a combination of several problems in the process from design to restoration (Kawai et al. 2014). Thus, simplistic restoration of damaged structures without a consideration of safety at the present state is inadvisable. Even when information on the structure is limited, it is important to verify the cause of the damage, evaluate the safety of the structure at the present state and in the future, and then consider the maintenance plan. As for the previous research on safety assessment of existing suspension bridges, Coletti (2002) conducted a full-scale loading test of a real bridge and compared it to the results obtained by the finite-element method (FEM). Chen et al. (2015) conducted structural health monitoring and obtained stress influence lines to estimate the structural condition of a suspension bridge. However, these studies are not always applicable to other bridges, considering that extensive loading tests by closing the traffic or advanced and complicated measuring systems are necessary.

This study proposes a rational and effective maintenance strategy for damaged suspension bridges by using the case of Twantay Bridge as an example. In this article, the term *damage* is defined as an aberrant condition occurring in any part of the bridge that was

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Note. This manuscript was submitted on August 29, 2017; approved on May 1, 2018; published online on August 3, 2018. Discussion period open until January 3, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Bridge Engineering***, © ASCE, ISSN 1084-0702.

not expected in the design, such as inclination of the main towers and cracks. Fig. 1 shows a flow of the maintenance proposed in this study. As for the existing structures, the presence of damage is first evaluated by daily inspection and/or monitoring. Once any damage is found, precise investigations are conducted, and the cause of the damage is verified. In addition, it is important to evaluate the structural performance at the present state. If the structural performance is not acceptable, countermeasures for upgrading the structural performance, such as repair and strengthening, should be conducted. In this study, verification of the damage progress was conducted for the Twantay Bridge with the use of a simple monitoring and safety assessment involving a combination of structural analysis with FEM and spatial information measurement by three-dimensional (3D) terrestrial laser scan (TLS). Finally, a maintenance scheme for the Twantay Bridge is proposed based on the results of the investigation in this study.

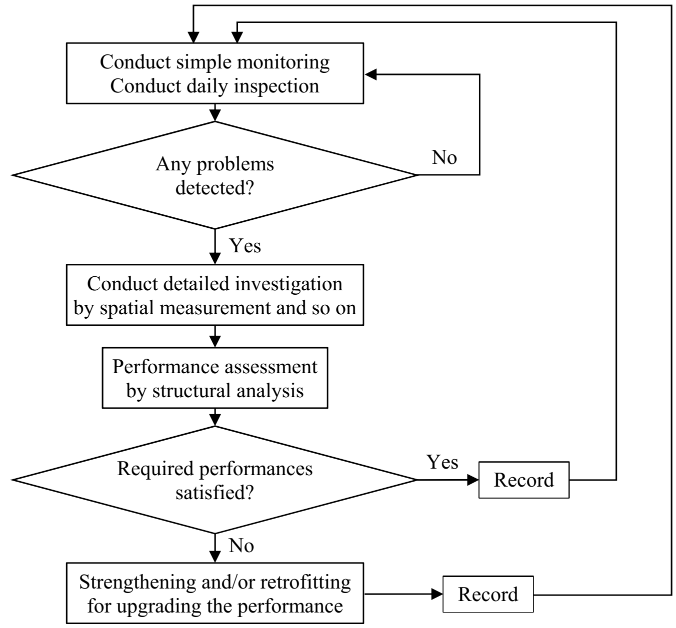

Fig. 1. Proposed flow of maintenance for damaged bridges in Myanmar.

Outline and Current State of the Twantay Bridge

The Twantay Bridge is a suspension bridge that was constructed in 2006 by the MOC, supported by China. Table 1 lists the design codes used for designing the Twantay Bridge. As shown in Fig. 2, the span length is 256 m, and the height of the steel main tower is 31.9 m. Fig. 3 shows the layout and details of the stiffening girders and main towers. The main cables are suspended by the north and south towers and fixed at the anchor blocks placed on the RC piles at the ends of the bridge [Fig. 4(a)]. It is reported that the anchor blocks were moved by the force of the main cables in the direction of the bridge axis because the region including the Yangon area is on alluvial ground with very soft soil conditions (JIP 2012). It is supposed that because the main towers and main cables are fixed at the top of the tower, the movement of the anchor block induces loosening of the main cable on the outside of the main span. The reduced tensile force of the main cable on the outside of the main span is applied to the main tower as an external force in the bridge-axis direction. Thus, the bending moment is applied to the main tower. The actual bending moment and amount of anchorage movement are unknown; however, the cracks observed in the support of the girders on the anchor block on the south side seem to indicate a slippage of the girders due to the anchorage movement [Fig. 4(b)]. Fig. 5 shows the boring data for the soil near the anchor blocks. The N value of the soil is nearly 1 until a depth of approximately 10 m from the ground surface, indicating that the soil conditions in this region are very soft.

Fig. 6 shows the main towers. It can be seen that especially the south tower is significantly inclined toward the main span in the bridge-axis direction. It is supposed that the main tower was bent by the force in the bridge-axis direction transferred from the main cable. From the site investigation, corrosion of the main tower and cracks of the concrete foundation were not confirmed. Therefore, in this study, an inclinometer was set on the south tower, and simple monitoring was conducted (details are given later in the article).

In addition to the inclination of the main towers, a change in the road-surface level was found. The MOC measured the level of the bottom of each hanger cable five times from 2006 to 2016 to evaluate the position of the girders in the vertical direction. Just after the measurement in 2006, concrete blocks with a total weight of approximately 300 t were placed as a bridge railing (Fig. 7). In the measurement in 2009, a reduction of the road-surface level was first found. The road-surface level was still decreased in the 2011 measurement. There is a possibility that the overweight due to the concrete blocks also affected the movement of the anchor blocks. Consequently, the MOC reduced the dead load by removing the

Table 1. Design criteria of Twantay Bridge

Design criteria	Code
Structural steel work	DIN 18800, Parts 1–3 (DIN 1990a, b, c)
Structural concrete work	AASHTO (1996) and ACI 318-89 (ACI 1992)
Design load	HS20-44 according to AASHTO (1996) (60-t heavy vehicle trailer convoy spacing 10 m apart along the centerline issued by the government of the Union of Myanmar)

concrete blocks used as the bridge railing, and measurement of the road-surface level was conducted again in 2012 and 2016. Fig. 8 shows the results of the measurement of the road-surface level. In the graphs in Fig. 8, average values between the upstream side and downstream side are shown. Approximately 200 mm of camber can be seen in the midspan in 2006; however, it becomes approximately 300 mm in 2009, indicating that the road-surface level decreased by approximately 500 mm at the maximum. The result in 2011 is almost the same as that in 2009. In 2012, the road-surface level increased as a result of the disappearance of the concrete blocks; however, it did not recover up to the original level observed in 2006. The latest result in 2016 also indicates that the road-surface level did not recover to the original level. This fact indicates that the reduction of the road-surface level was caused by not only the placement of concrete blocks but also other factors, such as the movement of the anchor blocks. This result is used for verifying the amount of movement of the anchor blocks in the validation of the FEM analysis later in the article.

Simple Monitoring of Main Towers by Inclinometer

For the Twantay Bridge, as the first step of the investigation, it was important to verify whether the damage progress was still ongoing.

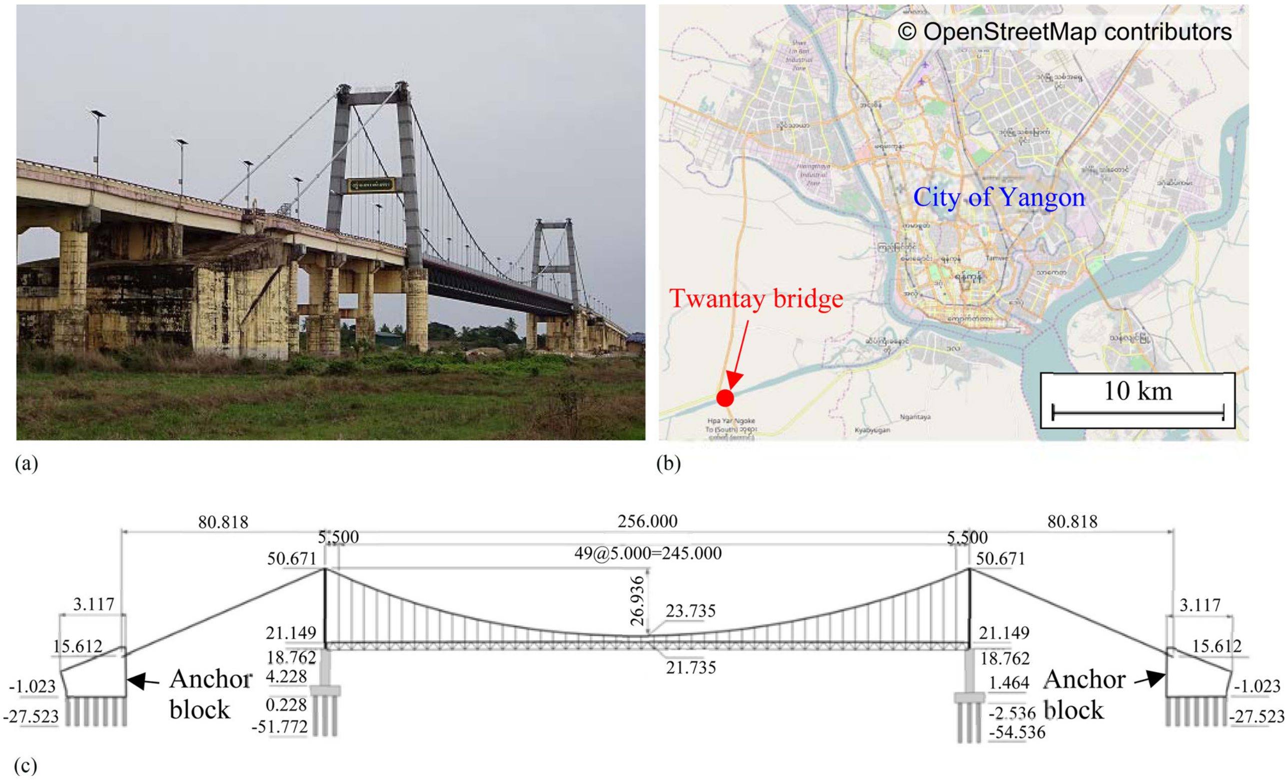

Fig. 2. Twantay Bridge: (a) photo (image by Kohei Nagai); (b) location (map data © OpenStreetMap contributors); and (c) drawing (side view).

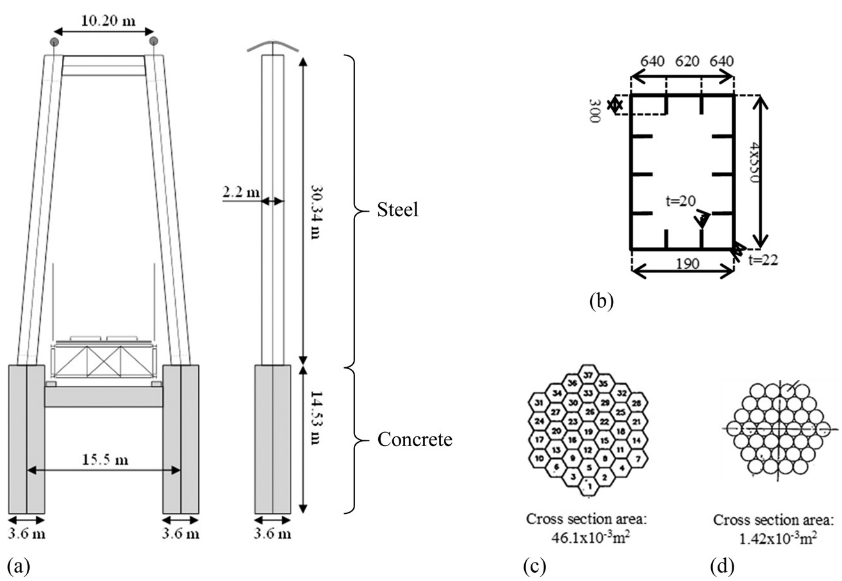

Fig. 3. Cross section and dimensions of main tower and cable elements: (a) dimensions of main tower; (b) main tower (steel part); (c) main cable; and (d) hanger cable.

In this study, an inclinometer was set on the south tower at the main-span side at approximately 10 m in height from the bottom of the steel part, as shown in Fig. 9. The inclinometer measures the inclination in both the bridge-axis direction and perpendicular to the bridge-axis direction. The resolution of the measurement is 0.0005 degrees. The atmosphere temperature is also measured. The measurement interval is 3 h. The measurement was started in May 2016 and was still continuing as of July 2017. The Yangon region has a rainy season from June to October, and it is expected that the movement of the anchor blocks is accelerated by a softer ground condition due to the rainfall. Therefore, the measurement was continued over 1 year to confirm the difference between the rainy season and the dry season.

Fig. 10 shows the measurement results from May 2016 to June 2017. Due to the deformation of the steel by temperature change, daily changes in the inclination can be seen. The amplitude of the daily change was found to be approximately 0.04 degrees. Considering the presence of the intermediate beam, the effect of the dimensions

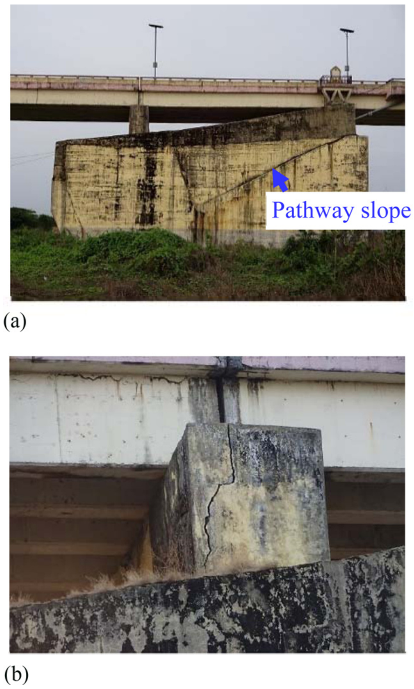

Fig. 4. Anchorage of Twantay Bridge (south side): (a) concrete anchor block; and (b) crack in column on the anchor block. (Images by Koji Matsumoto.)

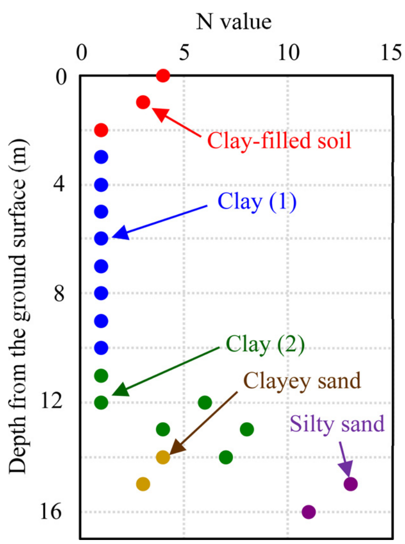

Fig. 5. Boring data near the anchor block.

and boundary conditions of the main tower on the measurement result of the inclinometer is complicated. However, as shown in Fig. 11, focusing on the relationship between the inclination degree and temperature, it is clearly seen that the inclination degree has a high correlation with the temperature in both the bridge-axis direction and perpendicular to the bridge-axis direction. In addition, the measured values from the inclinometer always recover to the initial state even though the inclination of the towers induced by the movement of the anchor blocks is considered to be an irreversible phenomenon, indicating that the main factor of the amplitude observed in the inclination is the temperature change. Thus, it was confirmed that the progress of the inclination of the main tower

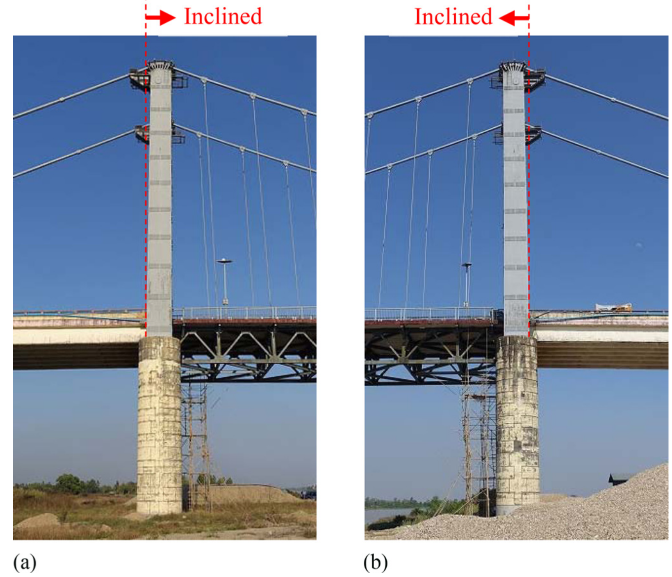

Fig. 6. Picture of main towers (as of September 2016): (a) north side; and (b) south side. (Images by Koji Matsumoto.)

was almost none within the 13 months of the measurement period. Therefore, because the safety at present was confirmed (as explained later in the article), it is supposed that emergency countermeasures are not necessary for the Twantay Bridge. However, when incidental external forces, such as earthquakes and cyclones, are applied, the monitoring result should be checked in each case. The amplitude of the inclination becomes bigger after November. This is because Yangon region enters the dry season in November, and the effect of the sunshine in the day time becomes significant.

Spatial Information Measurement by TLS

There are several methods for measuring the spatial information of structures. One of the most effective methods is TLS, which has millimeter-level accuracy. Several studies on the application of TLS to structures have been conducted, such as verification of the deformational behavior (Teza et al. 2016), damage detection in the surfaces of bridges (Liu et al. 2011), monitoring of the deformational change of structures over time (Park et al. 2007), estimation of building deformations in earthquakes (Pesci et al. 2013), and measurement of displacements in highway retaining walls (Oskouie et al. 2016). Compared with conventional displacement transducers and surveying, the advantages of TLS are as follows: (a) displacements in every location and direction can be captured; (b) measurements can be done rapidly and remotely; and (c) the absolute values of the displacement, rather than the change after the measurement started, can be obtained. This study used TLS to conduct spatial information measurement of the Twantay Bridge to clarify the actual deformational behavior of the main towers.

Outline of Measurement

The scanner measured range is 0.6–330 m, with a 300-degree vertical and 360-degree field of view. Six and eight scan locations were chosen for north and south towers, respectively. A 1/2 resolution at 488 kilopoints per second was used. All of the measurements were done by setting the TLS on the ground, as shown in Fig. 12. The 3D

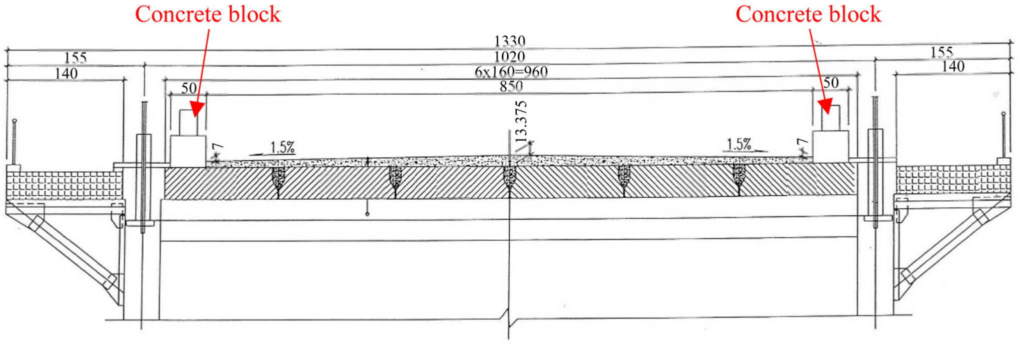

Fig. 7. Concrete blocks for original bridge railing (drawing of bridge cross section).

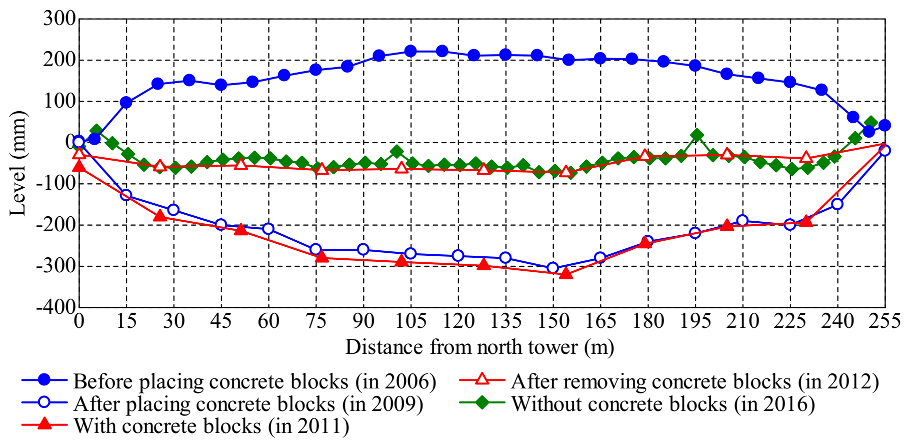

Fig. 8. Measurement results of road-surface level.

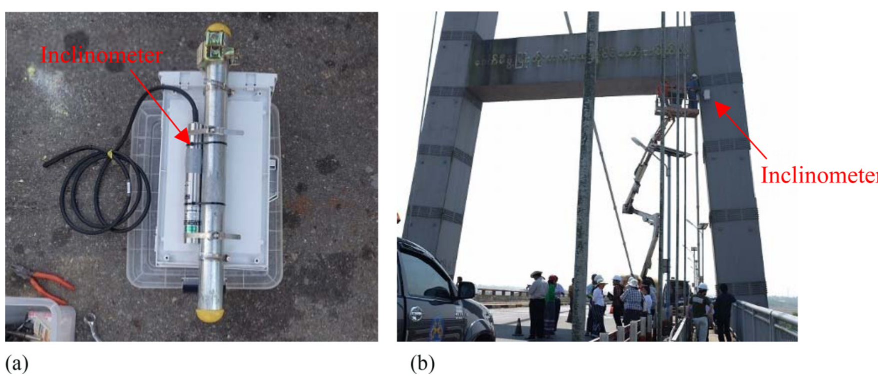

Fig. 9. Setting of inclinometer: (a) inclinometer with a box for data logger; and (b) fixing near the intermediate beam. (Images by Koji Matsumoto.)

point-cloud data of the Twantay Bridge were reconstructed by combining the point-cloud data obtained from each scan location.

Measurement Results

Point-Cloud Data

Fig. 13 shows the 3D point-cloud data of the Twantay Bridge, which were produced by integrating the measurement data obtained from each scan location. As shown in Fig. 13(a), this method accurately reproduced the overall geometry of the bridge. Figs. 13(b and c) show the appearance of the north and south towers, respectively, as viewed from the downstream side as shown in Fig. 6. The deformation of the main tower can also be clearly seen in the 3D point cloud. Even though this study focused on the geometry of the main towers, TLS can capture each member, such as main cables, hanger cables, girders, and so on. Therefore, this result can also be used to investigate other members according to the type of damage.

Assessment of Deformational Behavior of Main Towers

In this study, the deformational behavior of the main towers was evaluated by the following procedure, which is also explained in Fig. 14:

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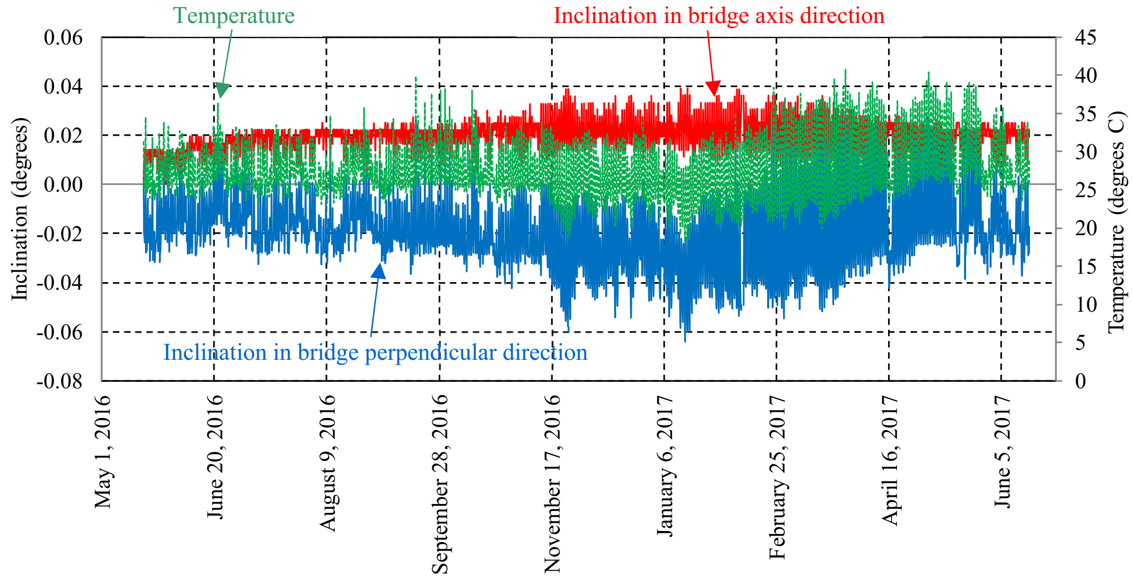

Fig. 10. Result of measurement by inclinometer.

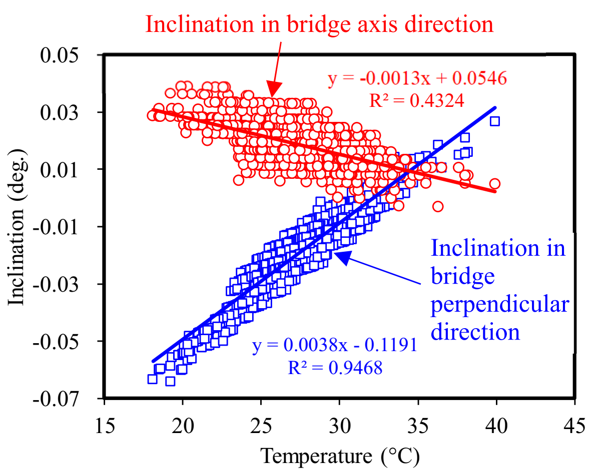

Fig. 11. Relationship between measured inclination and temperature.

- Step 1: The steel part of each tower (north-upstream side, north-downstream side, south-upstream side, and south-downstream side) was extracted from the 3D point-cloud data.
- Step 2: Surfaces on the north and south side were extracted for each tower.
- Step 3: The extracted point cloud was divided into 20 areas in the longitudinal direction, and the gravity point in each area was calculated. This division number is the same as the number of elements of the FEM model, as described later in the article.
- Step 4: Average points of north and south side were replotted. Consequently, the deflection distributions of the main towers were obtained.

Scan locations were only on the landside, and there were several masking objects, such as the intermediate beams and bridge decks, resulting in a nonuniform density of the point cloud of the main towers. A nonuniform point cloud affects the position of the gravity points. To eliminate the effect of the nonuniform density of the point cloud, Step 2 was conducted. The angle of the global coordinate system was determined by the level gauge equipped in the TLS. It was confirmed that the vertical positions at the bottom of the steel part of each main tower agreed with each other, indicating that the angle of the global coordinate system agreed with the actual horizontal and vertical direction.

Fig. 15 shows the deflection of each tower obtained by the proposed method. The difference between the upstream and downstream sides is small on both the north and south side, indicating that the main towers are inclined in the bridge-axis direction straightly, without a distortion. Focusing on the average between the upstream and downstream sides, the displacements at the top of the towers were found to be approximately 15 and 18 cm on the north and south side, respectively. To verify the nonlinearity of the main-tower deflection distributions, the average displacements are approximated by the following function:

$$\delta = az^3 + bz \tag{1}$$

where δ = deflection; a and b = constants; and z = distance from the bottom of steel part of the main towers.

Eq. (1) is based on the assumption that the tower deflection follows the cantilever system allowing an inclination at the bottom. The constant a represents the nonlinearity of the distribution, and the constant b represents the inclination at the bottom. The results of the approximation are also shown in Fig. 15. In the case of the north side, at the top of the tower ($x = 30$ cm), the linear component becomes 15.0 cm ($= 0.5 \times 30$), whereas the nonlinear component becomes only 0.87 cm ($= 3.24 \times 10^{-5} \times 30$). In the case of the south side, the linear component becomes 10.8 cm ($= 0.36 \times 30$), whereas the nonlinear component becomes 8.9 cm ($= 3.28 \times 10^{-4} \times 30$). These results indicate that the south tower is clearly curved, whereas the shape of the north tower is comparatively straight. If the boundary condition of the bottom of the steel part is assumed to be the fixed end (both horizontal and rotational directions are fixed), the steel part will exhibit the deformational behavior as observed in a cantilever system. Therefore, it is supposed that the inclination of the south tower was caused by the force in the bridge-axis direction at the top, whereas that of the north tower was not caused by such

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external forces. There is a possibility that the north tower was inclined from the beginning of the construction. This tendency agrees with the previous investigation (Kitratporn and Takeuchi 2016), indicating the high validity of the result. This result was used to estimate the movement of the anchor block by comparison with the FEM results, as discussed later in the article.

An inclination corresponding to 18 cm of displacement on the top of the main tower is approximately 0.4 degrees. This value is much larger than that induced by temperature (Fig. 11), indicating that the displacement at the top includes the effect of temperature change, but it is not significant for the safety assessment.

Fig. 12. Measurement by TLS in field. (Image by Koji Matsumoto.)

Assessment of Structural Performance by FEM Analysis

To clarify the present structural performance and ultimate limit state of the Twantay Bridge, FEM analyses were conducted. From only the information of the deformational state, the stresses in each member, such as the main cables and hanger cables, are unknown; therefore, it is difficult to evaluate the safety of the structure. Furthermore, from only the past records, it is difficult to verify what kind of processes the structure has undergone from the construction to the present state. Therefore, this study reproduced the behaviors from the construction stage to the present state with the use of numerical analysis. In the analysis procedure, first, the construction process of the dead-load application and the adjustment of the tensile forces in the hanger cables was reproduced, and the position of the cables and girders was determined (Steps 1 and 2). After that, concrete blocks were placed on the decks as the bridge railing (Step 3). Next, to reproduce the movement of the anchor block, forcible displacement in the direction to the main span was given to the nodal point of the anchor block on the south side. Last, comparing with the road-surface level measured by the MOC (mentioned earlier), the validity of the analysis method was confirmed, and the movement of the anchor block was verified (Steps 4 and 5).

Numerical analyses enable the estimation of stress conditions in each member, such as the main cables and hanger cables, which are

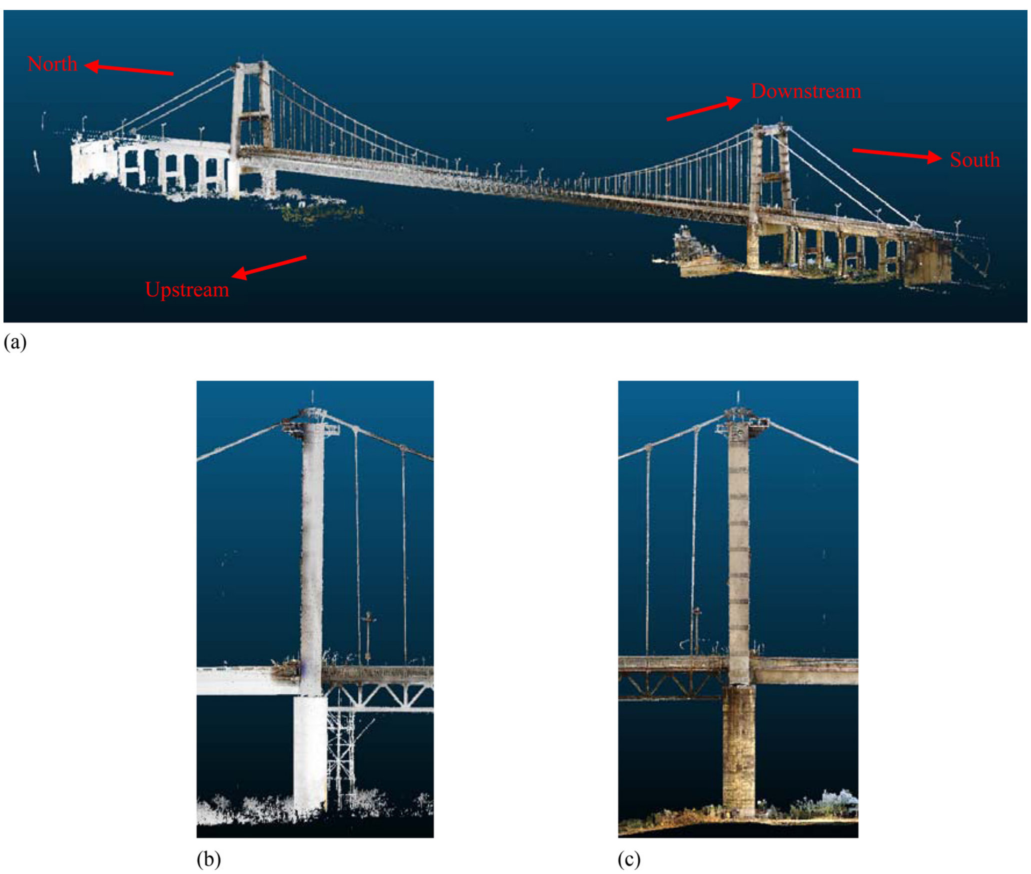

Fig. 13. 3D point cloud of Twantay Bridge: (a) overall appearance; (b) appearance of the main towers, north side (view from the downstream side); and (c) appearance of the main towers, south side (view from the downstream side).

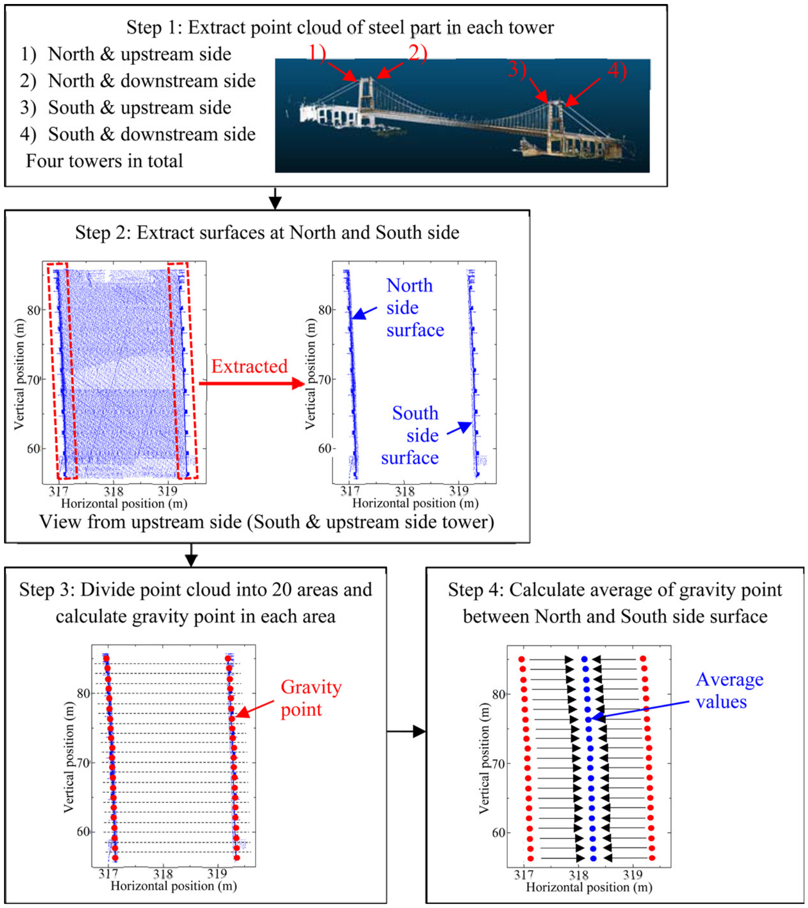

Fig. 14. Procedure for evaluation of deformational state of main towers.

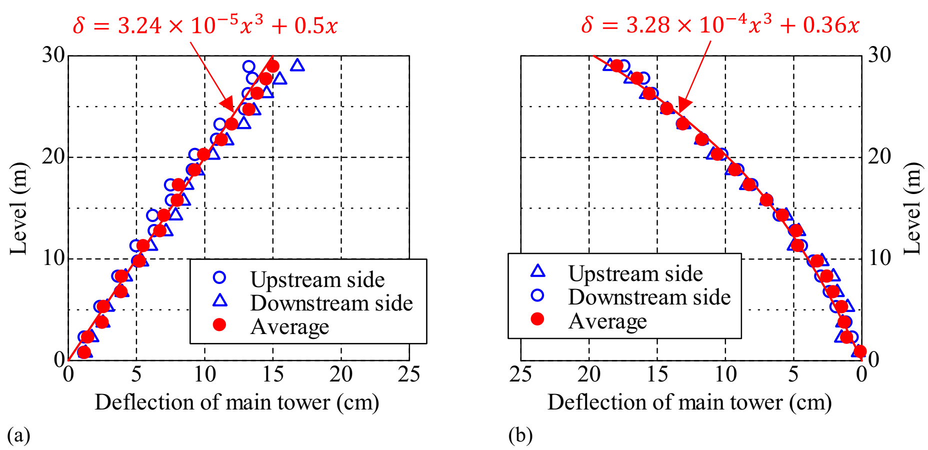

Fig. 15. Distribution of deflection in main towers observed by TLS (deflection toward main span is defined as positive value): (a) north side; and (b) south side.

difficult to measure in the field. In addition, by applying a load after inducing the damage, ultimate capacities can be computed, and the safety of the structure can be quantitatively evaluated. Furthermore, by increasing the movement of the anchor block, the structural performance in not only the present state but also the case in which the damage is further progressed can be verified.

In the analyses conducted in this study, FEM software was used in which the cable element with a pulley for stably determining the dimension of the cable structures and adjusting the tensile forces was implemented (Iwasaki and Nagai 2002; Dang et al. 2005).

Modeling of the Suspension Bridge

Fig. 16 shows the FEM model of the Twantay Bridge. Beam elements were used for the towers and girders, and cable elements

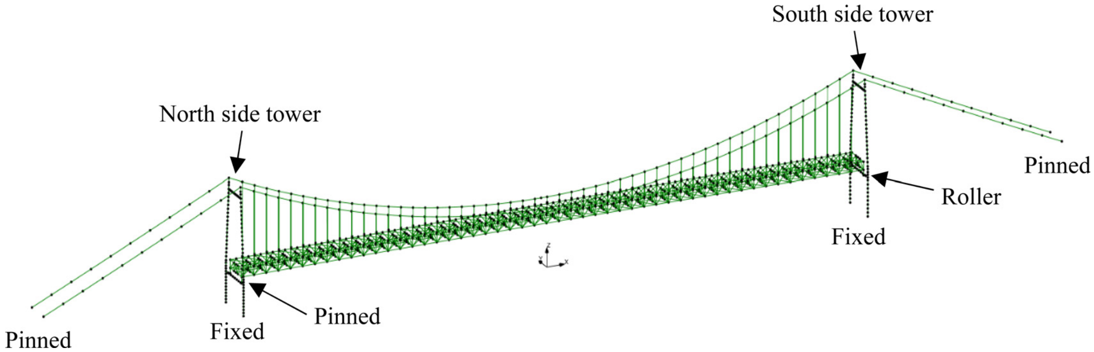

Fig. 16. FEM model.

Table 2. Material properties used in FEM

Structural member	Material property	Value
Main cable (37×PWS-61Φ5)	Elastic modulus	200 kN/mm^2
	Yield point	1,180 N/mm^2
	Tensile strength	1,570 N/mm^2
	Unit mass	361.9 kg/m
Hanger cable (PWS-37Φ7)	Elastic modulus	200 kN/mm^2
	Yield point	1,180 N/mm^2
	Tensile strength	1,570 N/mm^2
	Unit mass	11.2 kg/m
Steel of tower and stiffening girder (Q345c)	Elastic modulus	200 kN/mm^2
	Poisson's ratio	0.3
	Yield strength	325 N/mm^2
Concrete of tower	Elastic modulus	31 kN/mm^2
	Poisson's ratio	0.167

were used for the main cables and hanger cables. As for the boundary conditions, the bottom of the towers was the fixed end, and the anchorages fixing the main cables were pin hinges, respectively, according to the design. The girders were supported by a hinge and roller at the north and south sides, respectively. The main cable was assumed as being fixed by a hinge at the top of the main towers.

Table 2 provides the material properties of the steel used for the main towers, stiffening girders, main cables, and hanger cables. As shown in Fig. 17, the stress strain relationships used in the analysis were an elastoplastic model for the main towers and stiffening girders and a bilinear model for the main cables and hanger cables. The material nonlinearity (yielding) influences the result of the ultimate-state analysis.

Procedure of Analysis of Suspension Bridge Model

The analysis proceeded with a comparison of the design drawing and field-measured data in each step. The analysis procedure was as follows:

- Step 1: The dimensions of the bridge were determined so that the camber of the girder agreed with that in the design. After the dead load of the steel girders and RC decks in the part of the road was applied, the tensile forces of the main cables and hanger cables were determined so that the position of the girders and the top of the towers and the cable sag agreed with that in the design.
- Step 2: Remaining dead loads, such as the asphalt pavement and sidewalk, were added, and the road-surface level was compared with that measured in 2006.
- Step 3: Concrete blocks with a weight of 300 t were uniformly placed on the decks in the main span for the bridge railing, and the road-surface level was compared with that measured in 2009.
- Step 4: The anchor block on the south side was moved gradually, in 5-cm increments, and then the amount of the movement when the road-surface level agreed with that measured in 2009 was found.
- Step 5: After the concrete blocks were removed, the road-surface level was compared with that measured in 2012.

In the analyses, the movement of the anchor block was given by forced displacements (Step 4); therefore, behavioral changes over time, such as the creep of the soil, were not considered. Thus, the analyses in this study do not clarify the mechanism of the anchorage movement; however, the results can be used for safety assessment under the current conditions.

Results of Analysis

Change of Road-Surface Level

Fig. 18 shows the analytical results of the road-surface level together with the corresponding measurement results. The camber in Step 1 was determined by the dead load due to the steel girders and RC decks, whereas that in Step 2 was also affected by the other dead loads. In Step 2, it was confirmed that the road-surface level almost agreed with that measured in 2006, indicating that the analytical method used in this study was able to reproduce the construction process of the suspension bridge.

According to the result in Step 3, in which concrete blocks with a weight of 300 t were placed as the bridge railing, the road-surface level determined by the FEM was higher than that measured in 2009. This indicates that the reduction of the road-surface level was caused by not only the load of the concrete blocks but also the movement of the anchor block at this moment. Accordingly, in Step 4, the anchorage location of the main cable in the south side was moved, in 5-cm increments, toward the main tower. As shown in Fig. 18, when the anchor block was moved by 15–20 cm, the road-surface level was close to that measured in 2009. Consequently, the anchor block on the south side was supposed to be moved by 15 to 20 cm toward the main tower. The anchor block was further moved in the analysis. When the movement of the anchor block was 45 cm, yielding occurred at the bottom of the main tower. At this moment, the road-surface level decreased to approximately 60 cm in the lower direction.

After the anchor block was moved by 15 cm and the concrete blocks were removed in Step 5, the road-surface level was close to that measured in 2012 (just after the concrete blocks were removed). Thus, by giving the movement of the anchor block as the forcible displacement, the change of the road-surface level from the construction stage to the present was well reproduced.

Deformation of Main Towers

Fig. 19 shows the horizontal deflections of the main towers in each step. The deflection of the south tower was larger than that of the north tower because only the anchor block on the south side was moved in the analysis. The deflection of the south tower increased from Step 2 to Step 4, corresponding to the change in the road-surface level. The deflection decreased when the concrete blocks were removed in Step 5; however, the residual deflection still could be seen. This indicates that the effect of the movement of the anchor block on the deflection of the main tower was larger than that of the loading of the concrete blocks. Fig. 20 shows a comparison of the result in Step 5 and the deflection of the towers obtained from the TLS measurement. Focusing on the south tower, the deflection obtained from the measurement result by TLS was almost the same as that obtained in FEM, indicating the high validity of the FEM conducted in this study. Conversely, in the case of the north tower, the deflection obtained from the measurement result by TLS was larger than that obtained in the FEM. This is because only the anchor block on the south side was moved in the analysis, considering the possibility that the north tower was inclined during the initial construction.

As mentioned earlier, this study clarified that the validity of structural analyses and quality of construction can be verified based on the deformational behavior captured by TLS. This study focused on only the main towers, but verification of the other members, such as the main cables and hangers, is also possible.

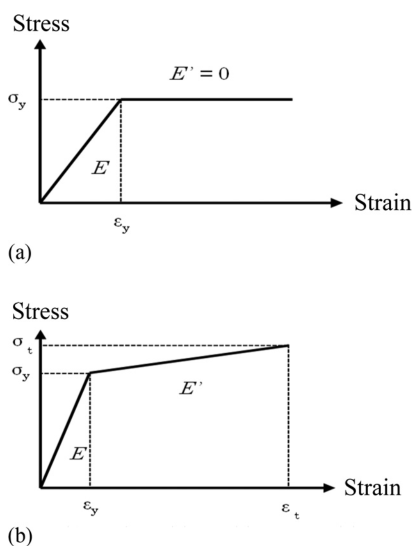

Fig. 17. Stress strain model for steel: (a) main tower and stiffening girder; and (b) main cable and hanger cable.

Assessment of Structural Performance

To evaluate the present structural performances of the Twantay Bridge, the tensioning condition and ultimate capacity were verified at the state in which 15 cm of forcible displacement were given to the anchor block and the concrete blocks were removed.

Tensile Forces in Main Cables and Hanger Cables

Figs. 21 and 22 show the tensile forces in the main cables and hanger cables, respectively, obtained in the analysis in each step. The movement of the anchor block did not strongly affect the tensile forces, whereas the presence of the concrete blocks had a significant effect on the tensile forces. This tendency is opposite that for the road-surface level. This is because tensile forces in cables are significantly affected by the weight of road-surface structures that are hung by the cables. In this state, the stresses of the cables were found to be almost the same as the original values (stresses in Step 2), indicating that the current condition of this bridge is safe in terms of the cable stresses.

Ultimate Capacity

To verify the safety of the Twantay Bridge after the damage was induced, an ultimate-state analysis was conducted. The load was applied by a combination of live loads and dead loads. The live load was determined following the AASHTO (2014) code, as shown in Fig. 23. The load factor α was multiplied by the applied dead load and live load, and the ultimate state was reproduced by increasing α.

Two cases of analysis, the sound model and the damaged model, were conducted. The sound model reproduced the state just after

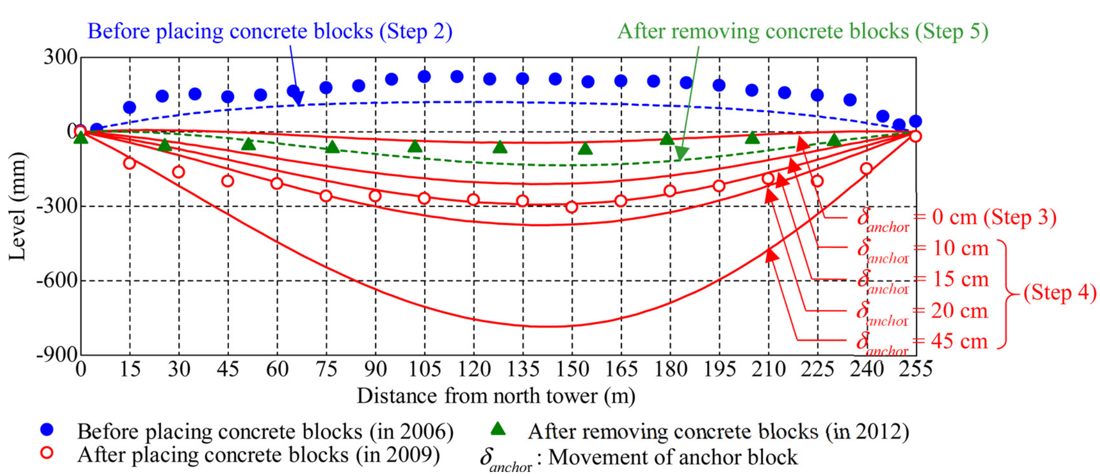

Fig. 18. Comparison of road-surface level obtained by FEM with measurement data (dots: measurement; lines: FEM).

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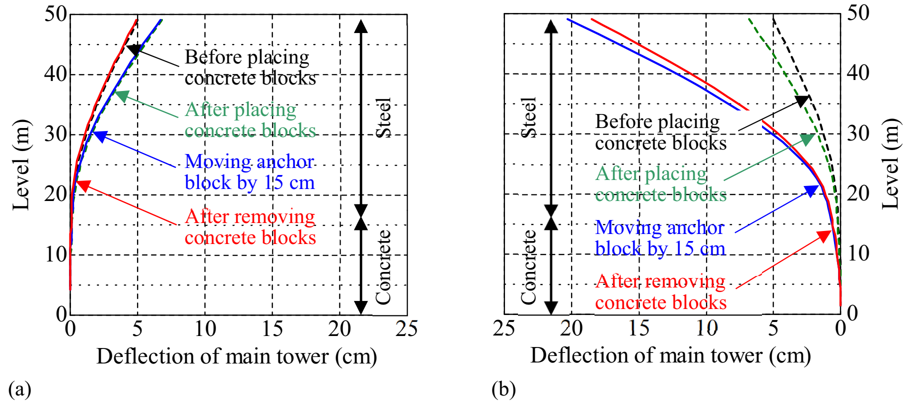

Fig. 19. Deflection of main tower in bridge-axis direction obtained by FEM (deflection toward main span is defined as positive value): (a) north side; and (b) south side.

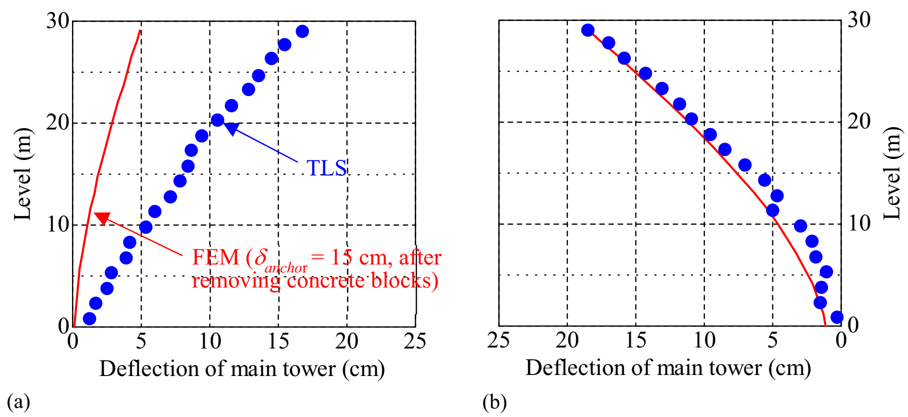

Fig. 20. Comparison of tower deflections between FEM and TLS results (deflection toward main span is defined as positive value): (a) north side; and (b) south side.

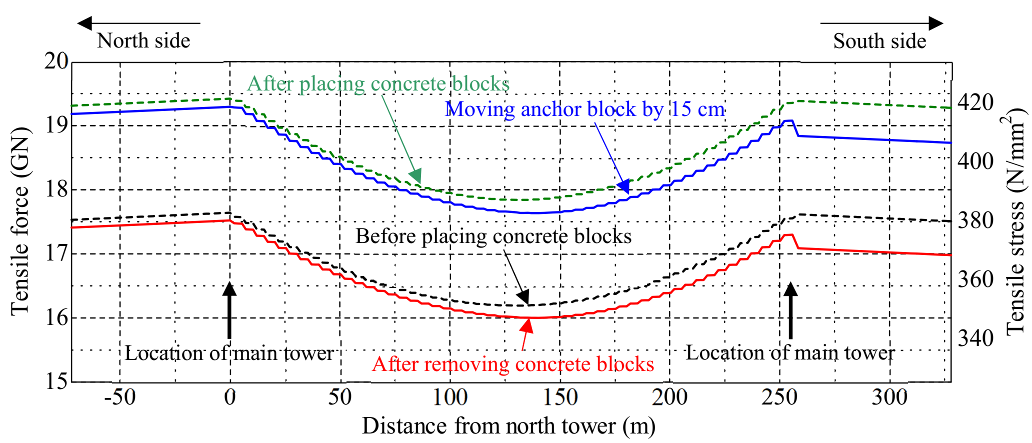

Fig. 21. Tensile forces and stresses in main cable obtained by FEM.

bridge construction, whereas the damaged model reproduced the present state. According to the results mentioned earlier, the anchor block on the south side was moved by 15 cm toward the main span, and the dead load was reduced by removing the concrete blocks in the damaged model.

Fig. 24 shows the load-factor α midspan deflection relationships obtained in the analyses. Under the same value of α, bigger deflection always occurred in the sound model compared with the damaged model. This is because the effect of the reduction of the dead load by removing the concrete blocks was more significant than that of the movement of the anchor block. Fig. 25 shows the transition of the yielding state of each member. Yielding occurred in the bottom of the steel part of the main towers first, the main cables second, and the girders last in both the sound model and the

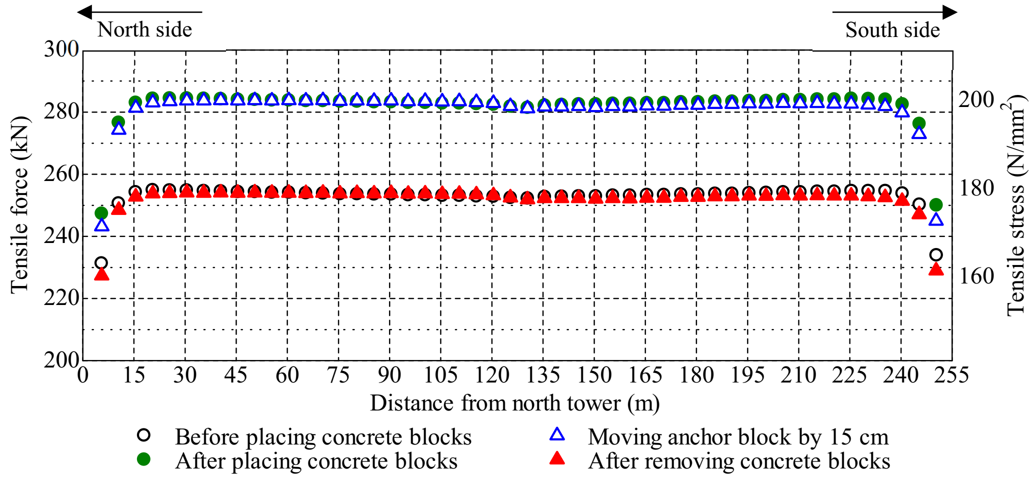

Fig. 22. Tensile forces and stresses in hanger cables obtained by FEM.

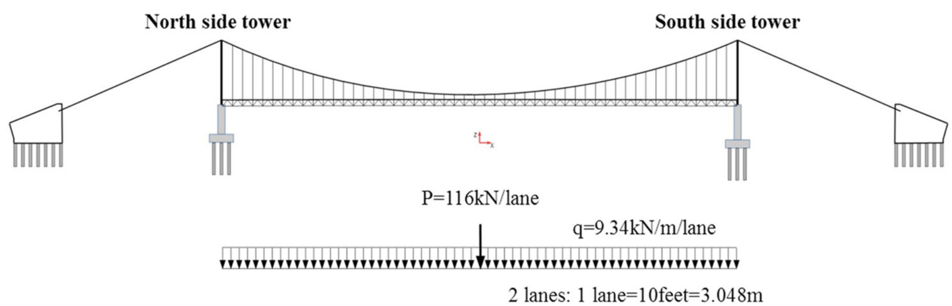

Fig. 23. Given live load.

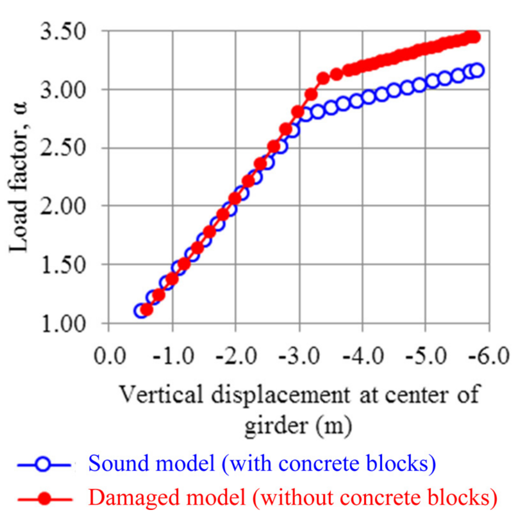

Fig. 24. Load factor displacement relationships in ultimate-state analysis.

damaged model. Focusing on the value of α when the bottom of the steel part of the main towers had yielded, $\alpha = 1.98$ in the case of the sound model, and $\alpha = 1.79$ in the case of the damaged model. This indicates that the ultimate capacity of the present Twantay Bridge is slightly decreased compared with the original one (just after the construction); however, the present capacity level satisfies the design criteria based on AASHTO (2014) LRFD specifications for the Twantay Bridge because the value of α in the damaged model is larger than the values of the load factors used for dead load and live load, 1.35 and 1.5, respectively. The analysis also revealed that the road-surface level decreased to approximately 3 m in the lower direction at the midspan when the yielding occurred at the bottom of the steel part of the main tower. This indicates that the ultimate state can be forecasted in advance by continuing the measurement of the road-surface level. The displacement at the top of the main tower when yielding occurred in the damaged model was approximately 30 cm, which corresponds to 0.6 degrees of inclination. This is 1.5 times larger than the current inclination (0.4 degrees). The monitoring by inclinometer mentioned earlier should be conducted considering this inclination level as the ultimate state.

This study verified the safety against the short-term loading. The long-term behavior, such as fatigue and corrosion of the steel due to water penetration at the location of local deformation at the joints or cracks, was not investigated. Considering that the environment around the Twantay Bridge is comparatively mild, the long-term behavior is not an emergent issue, but it is recommended that further investigations are taken into account in the future.

Proposal of Future Assessment Scheme

It was confirmed that the damage of the Twantay Bridge is not progressing at the present through simple monitoring using an inclinometer. In addition, it was confirmed that the present structural performance of the Twantay Bridge is satisfactory according to the results of the spatial information measurement by TLS and the

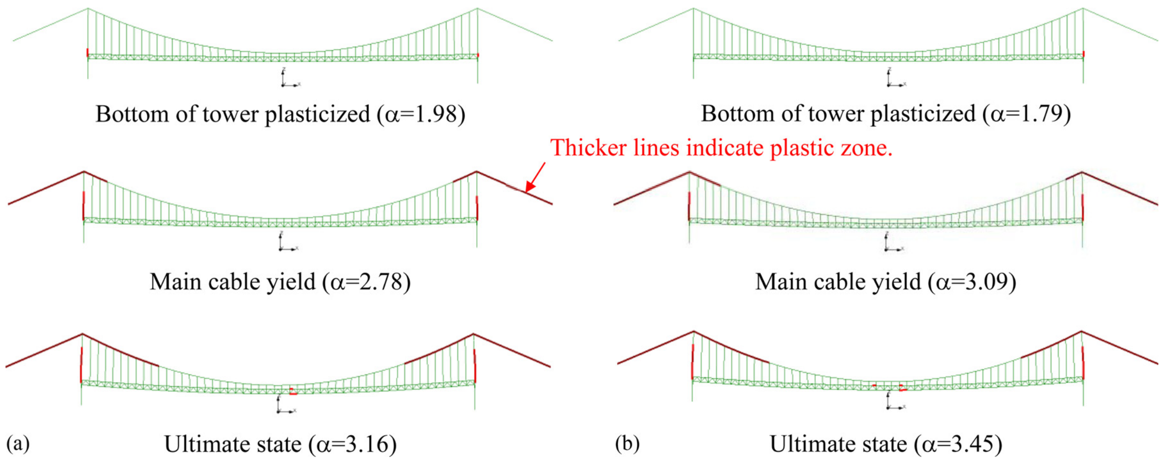

Fig. 25. Transition of yielding state: (a) sound model (with concrete blocks); and (b) damaged model (without concrete blocks).

structural analysis by FEM. For the maintenance strategy of the Twantay Bridge in the future, it is recommended to continue the monitoring of the inclination of the main tower and the measurement of the road-surface level. One of the optimum methods is that if any problems are detected by the monitoring, the TLS measurement is conducted again, and the safety of the bridge is verified based on the results obtained in the FEM analysis in this study.

Furthermore, considering that the soil conditions around the Yangon area are significantly soft, there is a high possibility that similar problems will occur in other bridges. It is also recommended that the initial condition is captured by spatial information measurement and other data just after the construction in addition to design and construction records to make it possible to compare the state after damage is induced with the initial one, especially for important structures.

Conclusions

This article proposes a performance assessment method composed of simple monitoring, spatial information measurement, and structural analyses for suspension bridges whose anchorages are moved by using the case of the Twantay Bridge in Myanmar as an example. From the results of the study, the following conclusions are obtained:

1. The result of simple monitoring by the inclinometer set on the inclined main tower confirmed that the damage in the Twantay Bridge is not in progress. This method is available for confirming the progression of damage in suspension bridges induced by soft ground conditions.
2. The overall geometry of suspension bridges can be measured by spatial information measurement using a 3D terrestrial laser scan. This article proposes a method for verifying the deformational state of the main towers of suspension bridges from point-cloud data. The proposed method can be applied not only to main towers but also to other members, such as main cables and hanger cables.
3. Finite-element method analyses were conducted to reproduce the behavior of the Twantay Bridge in the process from construction to the present state after the anchorage was moved. As a result, it was clarified that the road-surface level agreed with the measured values when the movement of one of the anchorages was approximately 15 cm. At this moment, the deflection of the main tower almost agreed with that measured by the 3D terrestrial laser scan, indicating that the actual amount of movement of the anchorage is approximately 15 cm. Accordingly, the analysis method conducted in this study can reproduce the deformational behavior of suspension bridges affected by anchorage movement. In addition, the FEM analysis revealed that the stresses and tensile forces of the main cables and hanger cables in the present Twantay Bridge are not affected by the anchorage movement. Furthermore, the FEM analysis for the ultimate state clarified that the ultimate capacity of the present Twantay Bridge is satisfactory for safety requirements. Thus, safety assessment of suspension bridges at the present state can be done by the method proposed in this study.
4. It is supposed that yielding will occur in the main towers of the Twantay Bridge when the anchorage movement reaches approximately 45 cm. This damage progress can be captured by simple monitoring. Consequently, this article proposes a maintenance scheme composed of simple monitoring, spatial information measurements, and structural analyses for damaged suspension bridges. This scheme is also available for newly constructed structures as a method that realizes a seamless transfer of the information in the construction stage to the latter maintenance stage.

As shown in this study, in some cases, combinations of existing technologies and tools can enable an approach to unsolved problems. This study focused on only the Twantay Bridge; however, the scheme proposed in this study, as a versatile method, can potentially be applied to other bridges in the future.

Acknowledgments

This research was supported by Science and Technology Research Partnership for Sustainable Development (SATREPS), Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA).

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