On-site visualization monitoring for long span bridge on Delhi Metro Project

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A new monitoring scheme, based on the concept of on-site visualization (OSV), was successfully applied for monitoring safety conditions during construction of a long span cantilever bridge in Delhi Metro Phase-II project in 2010. The bridge construction with challenging features included a 100 m long span over the Northern Railways tracks passing below, the balanced cantilever construction methodology with a see-saw condition of the pin-connected girder during segment casting processes and a horizontal curvature of the girder with 300 m radius. The light-emitting sensors with dual functions, namely sensing and simultaneous visual output of measured results, were employed in this project and played crucial roles to capture unique behaviours of the bridge under construction and to ensure safety throughout the project.

Keywords: Balanced cantilever construction, laser pointer, long span bridge, on-site visualization.

AN accident during construction of long span bridges would often lead to catastrophic collapse and loss of properties and human lives. For example, in the accident of Can Tho Bridge (cable stay bridge with 550 m centre span), 100 km south of Ho Chi Minh City, Vietnam in 2007, the collapse of supporting temporary steel trestles and supporting steel beam together with fresh concrete girder resulted in a massive fatal accident with 2 years delay and huge additional cost[1].

Long span bridges, including suspension bridge, cable stayed bridge and box girder bridge become rigid and stable after completion of construction. However, these long bridges could be instable during construction stages (Figure 1)[2]. Any unbalanced loading caused by dead load, live load, structure deformation and ground settlement can lead to catastrophic failure of the total structure. In Vietnam, the requirement of loading test for bridge structure and supporting structures is specified in Industrial Standard[3] and its application became more strict after the Can Tho Bridge accident.

After the Great Hanshin Awaji Earthquake in 1995, Japanese safety standard for seismic design of bridges was dramatically improved in order to maintain lateral resistance of structure under large earthquake during operation stage as well as construction stage[4]. In India, after encountering bridge accidents at construction stage as described below, Delhi Metro Rail Corporation Ltd (DMRC) improved the design procedure for elevated section from the Contractor's design to DMRC's direct design and appointed international consultant. In Singapore, after the Nicoll Highway Collapse during metro construction, the Land Transport Authority (LTA) strictly applied the 'one strut failure' rule into their temporary design, namely providing some redundancy into the design such that failure of any one support would not lead to overloading and progressive failure of adjacent members or catastrophic failure during construction[5].

Long span bridge on Delhi Metro project

Delhi Metro Phase II, urban mass rapid transit project implemented by DMRC, covering 120 km stretch from central Delhi to suburb regions funded by Japan International Cooperation Agency (JICA) was completed in 2010 (ref. 6), just before the Commonwealth Games in

Figure 1. Bridge collapse during construction stage[2].

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Delhi. Under a tight construction schedule, there were two fatal bridge accidents, namely collapse of steel launching girder at a viaduct bridge section in 2008, and the collapse of cantilever pier cap at a viaduct bridge section in 2009. They became one of the main reasons that DMRC decided on the application of a monitoring scheme under JICA SAPI Project[7], characterized by the use of light-emitting sensors for the safe construction of long span bridge at Okhla (Okhla bridge; Figure 2). The main engineering features of Okhla bridge are:

- The 100 m long span bridge over the Northern Railways tracks passing below the bridge.
- The balanced cantilever construction methodology for its construction in order not to hamper the railway traffic below, applying a bridge builder that constructs the bridge segment by segment at a time.

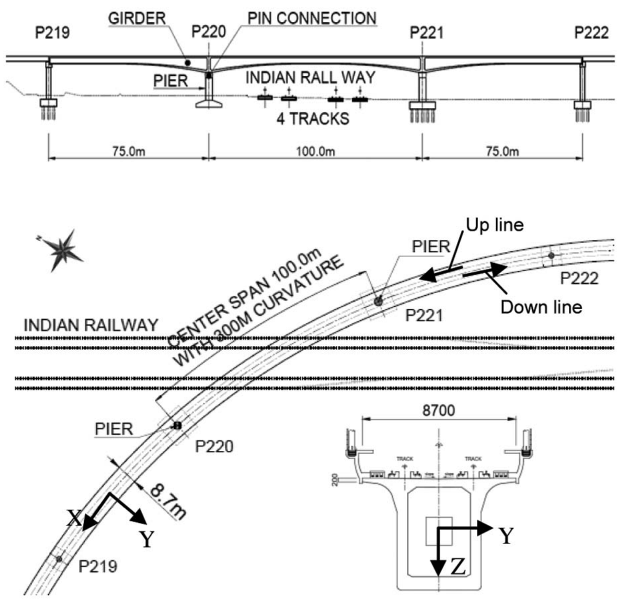


Figure 2. Plan and section of Okhla bridge.

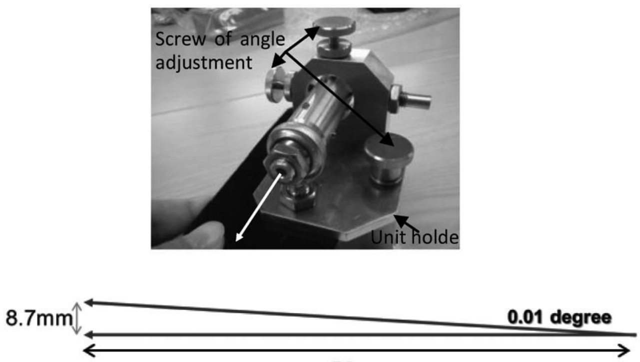


Figure 3. Laser pointer for inclination monitoring.

- The very steep horizontal curvature of the bridge with 300 m radius and no symmetrical loading of bridge segment castings against longitudinal bridge axes.
- A see-saw condition of bridge loading during segment construction because the connection of girder and pier is a pin joint by bearing point.
- The bridge construction under day and night (24 hours per day) working.

On-site visualization monitoring

A monitoring method, called on-site visualization (OSV), has been developed in Japan[8,9]. It has already been applied successfully at construction sites of slope excavation, tunnel excavation, concrete pressure monitoring and bridge construction in Japan[10]. The core concept of the OSV as a new form of engineering monitoring is that the sensors used have a newly added function of emitting measured information as the colour of an LED or another form of light-emitting device. Therefore, as the changes in monitored displacement, strain, inclination, etc. occur, they are processed instantaneously and emitted as the colour of, for example, LED lamps to people nearby. The speed required for another monitoring system to give an emergency warning signal or message to nearby citizens and construction workers, might be greater than the capability even for a very advanced monitoring system. The monitoring by OSV makes real-time 'monitoring and disclosure of measured data' possible. The devices which have been applied at construction sites so far are shown in Table 1.

The critical behaviour of Okhla bridge is a see-saw condition of the girder during segment construction. Therefore, OSV devices for inclination monitoring, namely laser pointer and light-emitting inclination sensor (LEIS) were selected for the safety monitoring of Okhla bridge.

The laser pointer could be an easy-to-handle inclination sensor. For example, a laser pointer that experiences

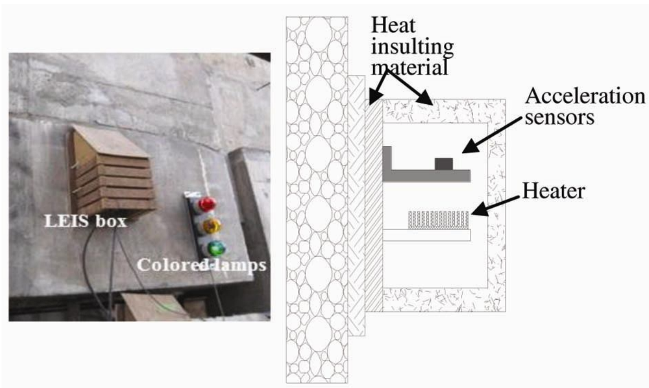
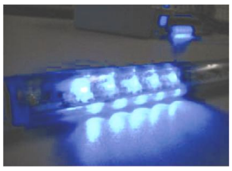
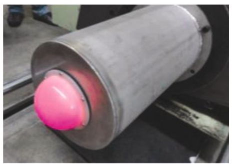


Figure 4. Light-emitting inclination sensor with coloured rotation lamps.

Table 1. On-site visualization devices applied at construction sites

OSV device	Specifications
	Light-emitting deformation sensor (LEDS): The LEDS, the first such device in the world, as a deformation sensor with an added function of outputting the measurement result by the colour of light-emitting diode (LED), was first developed in 2007 and has been modified several times while it has been used in the field tests in tunnelling, open excavation in urban areas, old cut slopes, etc.
	LEDS for rockbolt: The modified LEDS for rockbolt was developed and tested in the laboratory. In this example, three relative displacements were measured from one rockbolt and their colours were shown in the LED unit box outside the rock mass. Further cost reduction and simplification of the device is awaited for field application.
	LEDS for anchor bolt: The modified LEDS for ground anchor was developed and tested in the laboratory. Generally, estimation of axial force of a ground anchor requires use of oil jack and manpower, and it is a costly practice. Once the newly developed LEDS for a ground anchor is installed, its axial force in a usual condition, or after heavy rain, earthquake, etc. can be simply visualized by the colour of LED attached on its cap.
	Light-emitting inclination sensor with coloured rotation lamps: Accelerometers were used as key sensors to measure inclination which is shown by rotation lamps of different colours. The censing unit made up of accelerometers is generally used for automobiles. Two such units with a temperature control unit were boxed in a single container that was connected to the light-emitting part made of three rotation lamps. Field application example in Japan has not yet been conducted.
	Light-emitting converter with arbitrary sensor: The most recent development made by the OSV consortium is a new type of data converter which can log data from an arbitrary measurement device and show the results with an LED attached to it. By using this data converter, called a light-emitting converter, with a designated sensor (which could be for measuring strain, displacement, earth pressure, water pressure, temperature, etc.), almost anything can be measured and its result shown by the colour of LED in real time.
	Laser pointers: These are also used as auxiliary light-emitting devices. A laser pointer itself is not a sensor, but it can be used as a visual tool to show inclination or deformation of a point of installation. Simple experiments and a field test have been conducted in Japan.

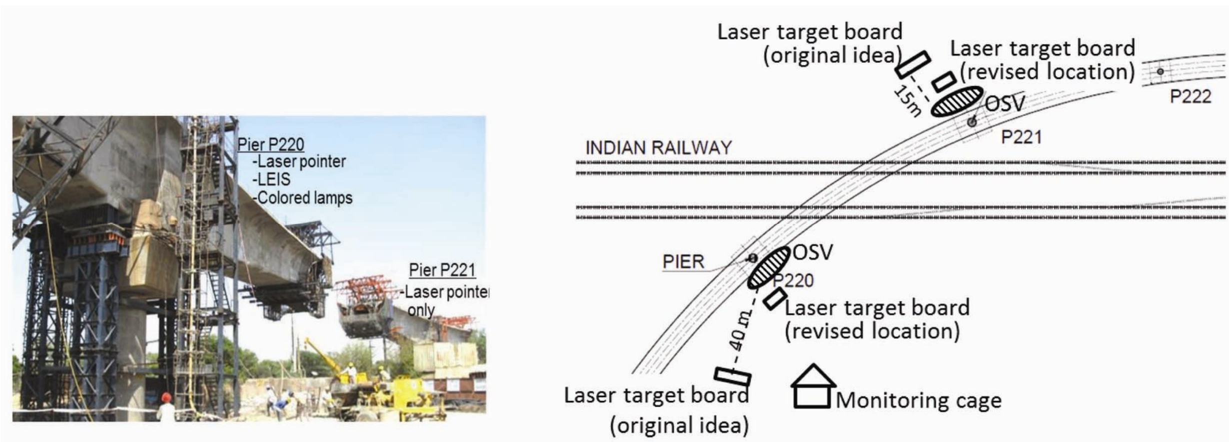


Figure 5. Arrangement of on-site visualization monitoring at site.

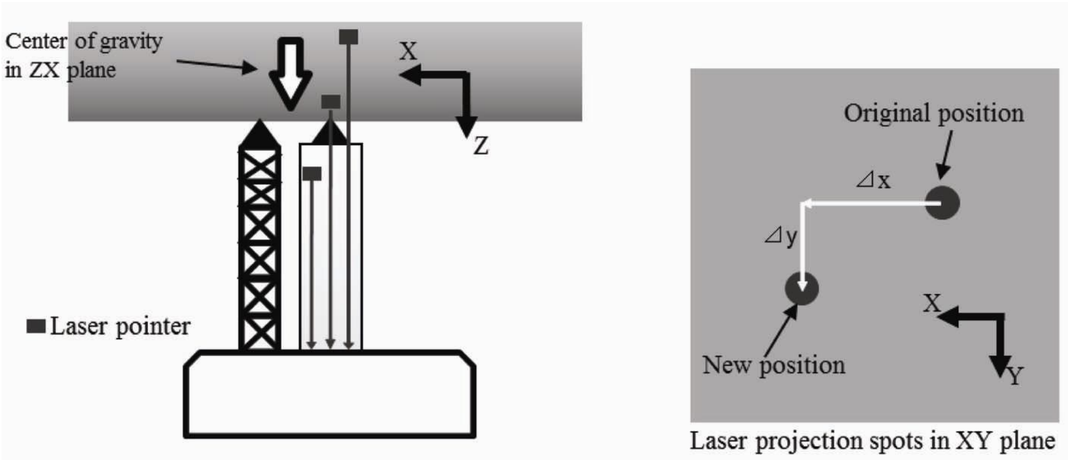


Figure 6. Schematic layout of laser pointers at P220 and P221.

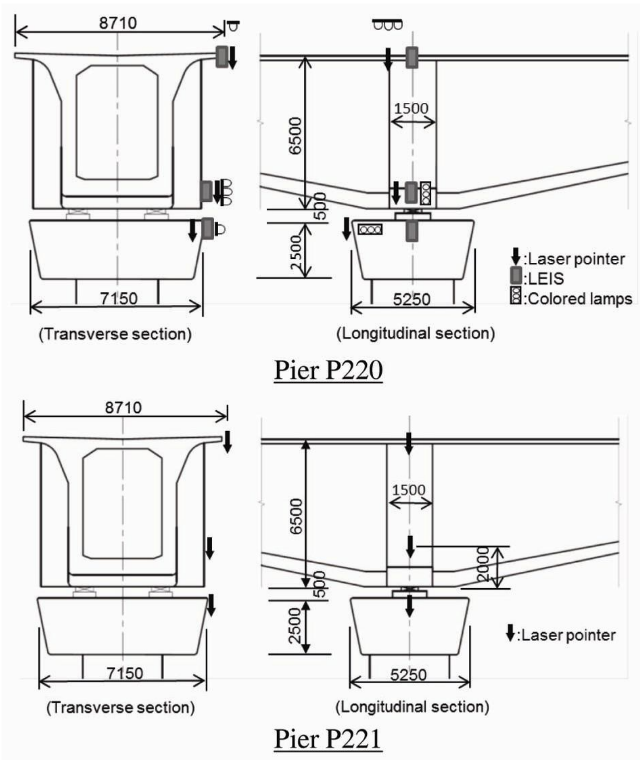


Figure 7. Detailed position of OSV devices at P220 and P221 (dimension in mm).

rotation of 0.01° moves its projected beam spot by 8.7 mm on a screen 50 m away from the pointer. If greater magnification is needed, the screen can be placed further. To assure reliable fixation of a pointer at a given point, the special designed holder unit for each perpendicular direction could be used as shown in Figure 3.

LEIS has two acceleration sensors in the sensor box[11]. They are designed to measure inclination angles in the *XZ* plane (θ_{xz}) and *YZ* plane (θ_{yz}) respectively. The data of each plane inclination are recorded individually and the safety evaluation is conducted based on each directional inclination as follows

$$\theta_{\max} = \text{SQRT}(\theta_{xz} + \theta_{yz}).$$

The maximum gradient computed from them is calculated and compared with pre-defined trigger values to determine the corresponding three colours, namely 'green', 'yellow' and 'red' of rotation lamps (Figure 4). LEIS is equipped with a heater and automatic temperature control function at 50°C constantly in order not to be affected by surrounding air temperature.

Figure 5 shows the arrangement of the OSV monitoring devices, laser target boards and monitoring cage. The monitoring face was carefully decided not to disturb the Indian Railway operation by OSV coloured lamps. Initially, target boards of laser pointers were kept at certain distances, namely 40 m at P220 and 15 m at P221 respectively. Based on the trial reading, it is recognized that the girder inclination is relatively large and relatively short distance from the laser pointers to the boards is sufficient to measure the girder inclination. Therefore, the locations of laser boards were shifted to pier bottom for easy measurement at site. Figure 6 shows the schematic layout of the laser pointers and shifts of the laser beam spot both in the *x* and *y* directions. Inclination in the *XZ* and *YZ* planes could be computed for comparison with the data obtained from LEIS.

Figure 7 shows detailed position of OSV devices. Pier P220 was chosen as the main monitoring target where its stage-by-stage inclination was monitored by three LEIS and three laser pointers. Pier P221 was monitored for inclination by three laser pointers only. The first two (named 'girder top' and 'girder bottom') were mounted on the side face of the girder and expected to pick up respective inclination at each stage of concrete casting. The third sensor (named 'pier top') was mounted on the side face of the pier head rigidly connected to its large

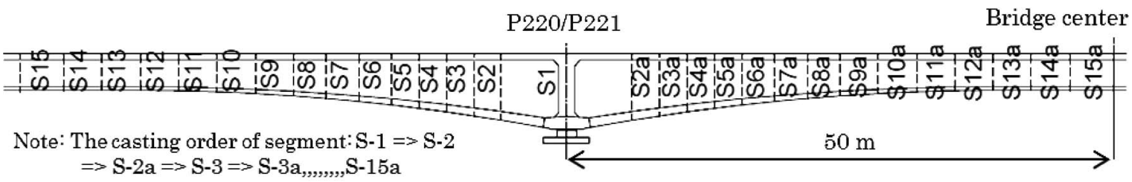


Figure 8. Order of segment casting by balanced cantilever construction methodology.

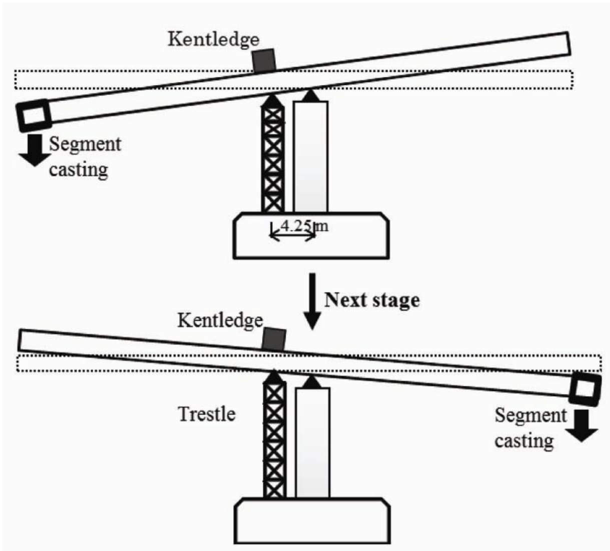


Figure 9. See-saw condition of bridge girder at each construction stage.

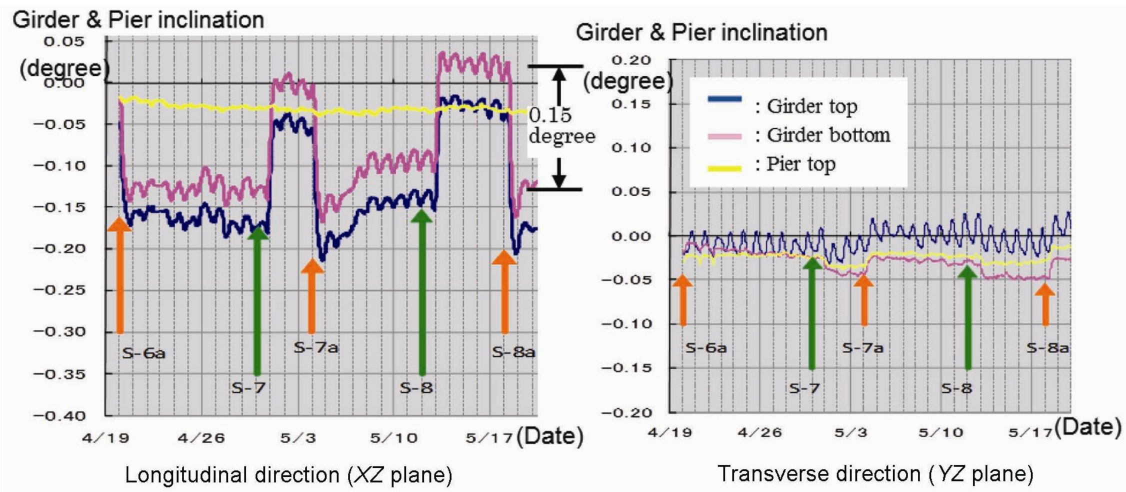


Figure 10. LEIS reading for the first month at P220.

concrete foundation. The foundation of P220 is raft foundation (no pile) and that of P221 is bored pile foundation as shown in Figure 2. The inclination at ‘pier top’ was expected to be very small, according to design.

Construction method and OSV monitoring

As shown in Figure 8, the casting order of concrete segment at site is ‘S1, S2, S2a, S3, S3a… up to S15a’ to maintain the total loading balance of the girder. The girder length of cantilever portion is 50 m under R-300 m horizontal curvature and the centre span length between P220 and P221 is 100 m after bridge centre connection. The bridge girder was always in a see-saw condition by the balance cantilever construction method as shown in Figure 9. The structural connection between bridge pier and girder was a pin joint and temporary steel trestles were installed to support the girder for the structure balance during segment casting under a see-saw condition. A

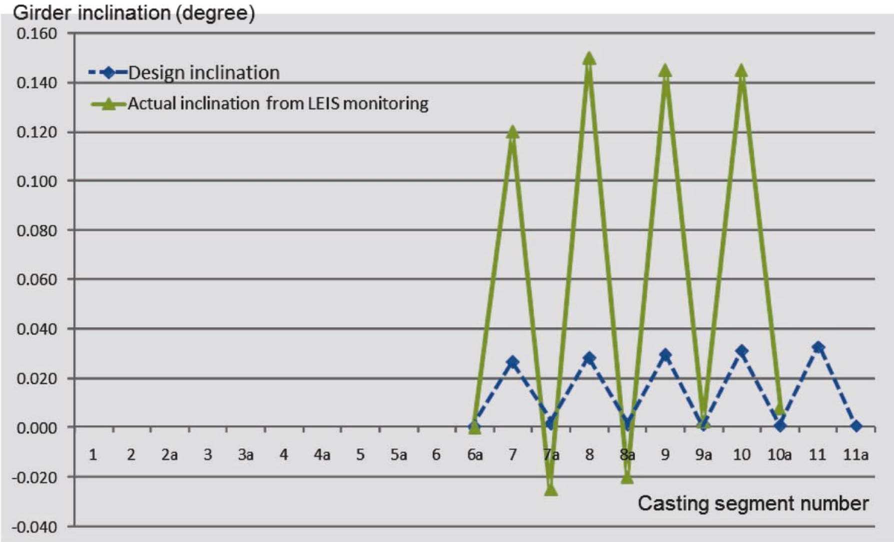


Figure 11. Bridge girder inclination on longitudinal direction (*XZ*) at each stage at P220.

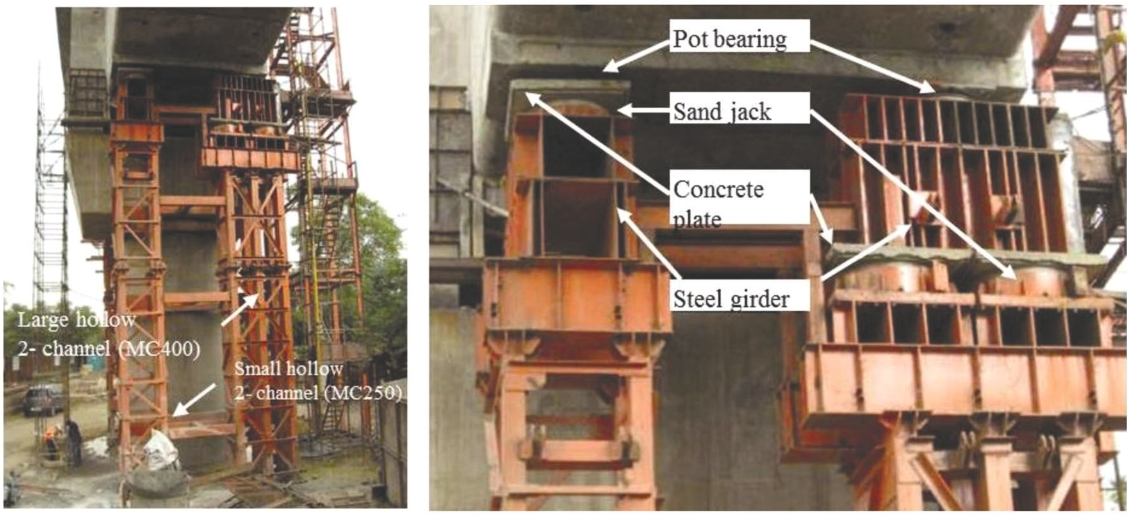


Figure 12. Details of temporary steel trestles.

20 tonne kentledge was set on the girder above the trestle location to prevent the girder moving down to the Indian Railway side.

LEIS reading and compression stress reading of steel trestle

The LEIS reading was started on 19 April 2010 from segment casting at S-6a (Figure 8). For the first month, the measurement of LEIS was conducted without activating the light-emitting function to compare the design value with actual girder inclination. During this period five segments namely S-6a, S-7, S-7a, S-8 and S-8a were casted as shown in Figure 10. In this stage, the casting girder was still short and there was no safety concern to operate the Indian railway below. Two steel trestles consisting of six and four hollow sections respectively were activated as temporary girder support during concrete segment casting. The design inclination of the girder in the *XZ* plane was calculated by frame analysis, namely differential elastic settlement (compression) between pier column and steel trestles. The inclination was calculated from segment S6-a condition and the value became 0.03° approximately due to stage-by-stage casting of girder segment. However actual inclination was very large, in the order of 0.15° as shown in Figure 11. Besides, regardless of very large inclination of the girder, the monitored actual stress on the steel trestle by strain gauge monitoring was very small; it was only 21 N/mm^2 on average and only 15% of its allowable stress.

Figure 12 shows the connection detail between steel trestles and bridge girder. It consists of pot bearing,

Figure 13. OSV safety board showing safety action plan and site audit at site.

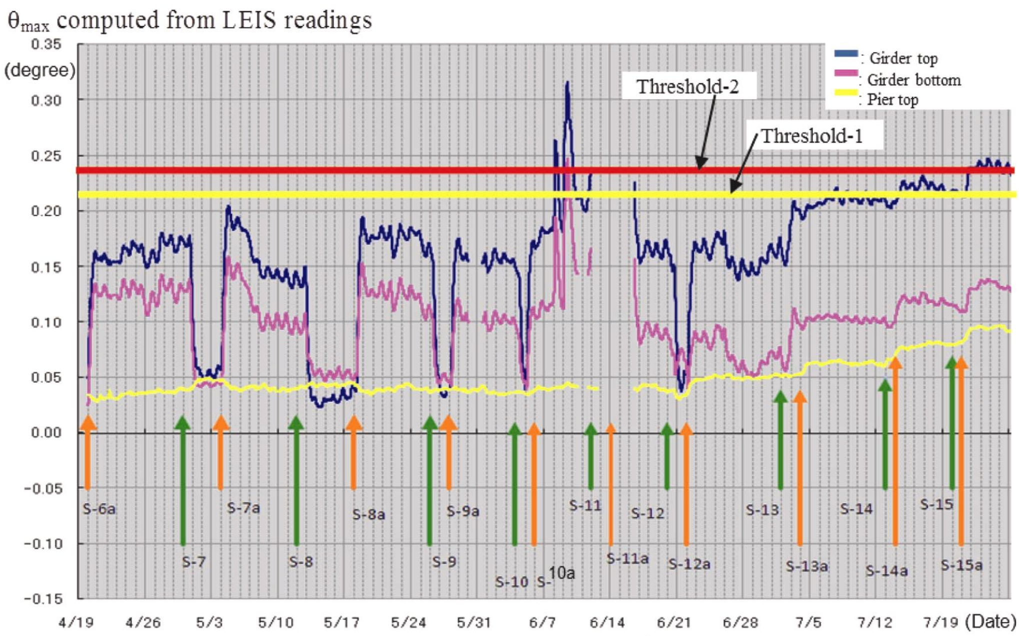


Figure 14. Maximum inclination (combined *XZ* and *XY* planes) by LEIS at P220.

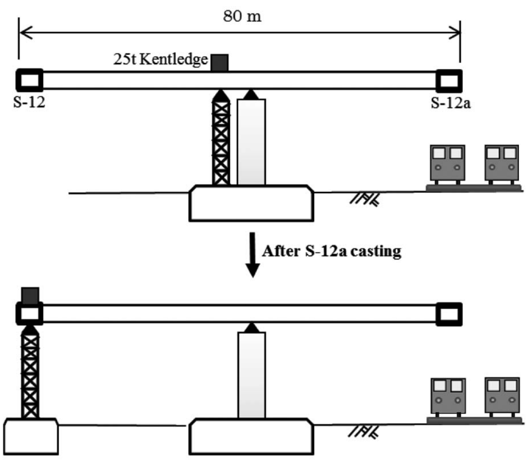


Figure 15. Shifting temporary support after segment casting S-12 and S-12a.

concrete plate, steel girder and sand jack. The possible cause of large inclination of girder is the existence of slack (gap) at the sand jack portion under insufficient sand compaction. Although the connection was tightened manually, no jacking-up procedure was followed quantitatively to ensure sufficient initial pre-loading.

Threshold values for colour scheme

Based on the above observation, the actual magnitude of girder inclination was found to be larger than design prediction and the threshold values for the final colour schemes were determined as follows:

Threshold-1: 0.15 + 0.07 = 0.22°.
(The trestle stress reaches 80% of allowable stress under 0.07° increase.)

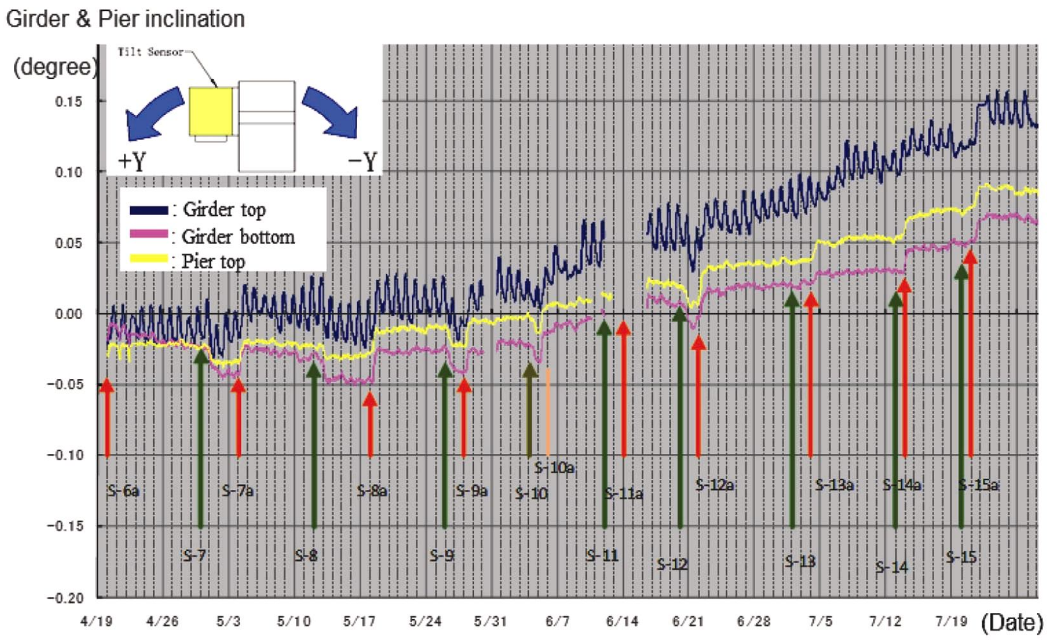


Figure 16. LEIS reading on transverse direction (*XY*) at P220.

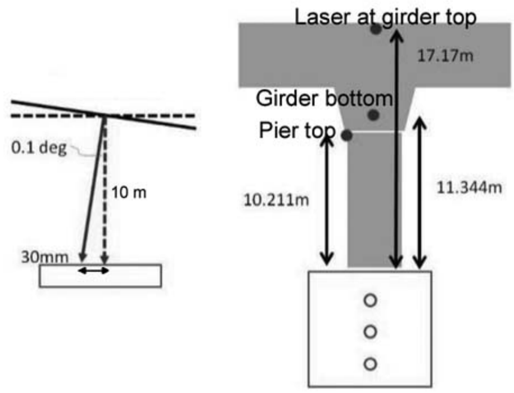


Figure 17. Concept of laser pointer reading.

Threshold-2: 0.15 + 0.09 = 0.24°.

(The trestle stress reaches 100% of allowable stress under 0.09° increase.)

The site action plan was made as follows:

(1) 'Keep working', if the inclination is less than threshold-1.
(2) 'Report to safety manager and confirm the next action', if the inclination is between threshold-1 and threshold-2.
(3) 'Keep clear (run away)', if the inclination is greater than threshold-2.

The safety induction talk was conducted inviting all site staff and the OSV safety plan was explained using a notice board as shown in Figure 13.

Maximum inclination of girder and pier column at Pier 220

Based on the above definition of threshold values, the OSV monitoring was restarted from segment S-9 up to completion of construction stage. Figure 14 shows θ_{max}. Theoretically, this value should be little different from one-directional reading because design calculation shows almost no inclination for the *YZ* plane. It is clear that LEIS has captured real behaviour of the bridge because segment casting date matched exactly with the timings of recording large response from the sensors. The inclination is well under the threshold values during most of the construction time. However, just after segment casting at S-10 and S-10a, the inclination increased dramatically and became larger than threshold-2.

The colour of rotation lamps was quickly changed from 'blue' to 'yellow' and from 'yellow' to 'red' at pier top and pier bottom based on the report from workers to safety manager. This excessive inclination was toward the Indian Railway side and careful operation was required. The construction activities were stopped and the counter measure, namely an increase of kentledge above the temporary trestle from 20 to 25 tonne was executed. It had an effect to reduce the inclination tendency towards Indian Railway side and the value was reduced successfully to continue the next girder construction.

As an additional counter measure to stabilize the longitudinal see-saw phenomenon of the girder, the steel trestle was shifted and replaced as shown in Figure 15 after segment casting S-12 and S-12a. Obviously the girder movement became stable and there was no more see-saw phenomenon after S-12a casting as shown in Figure 14.

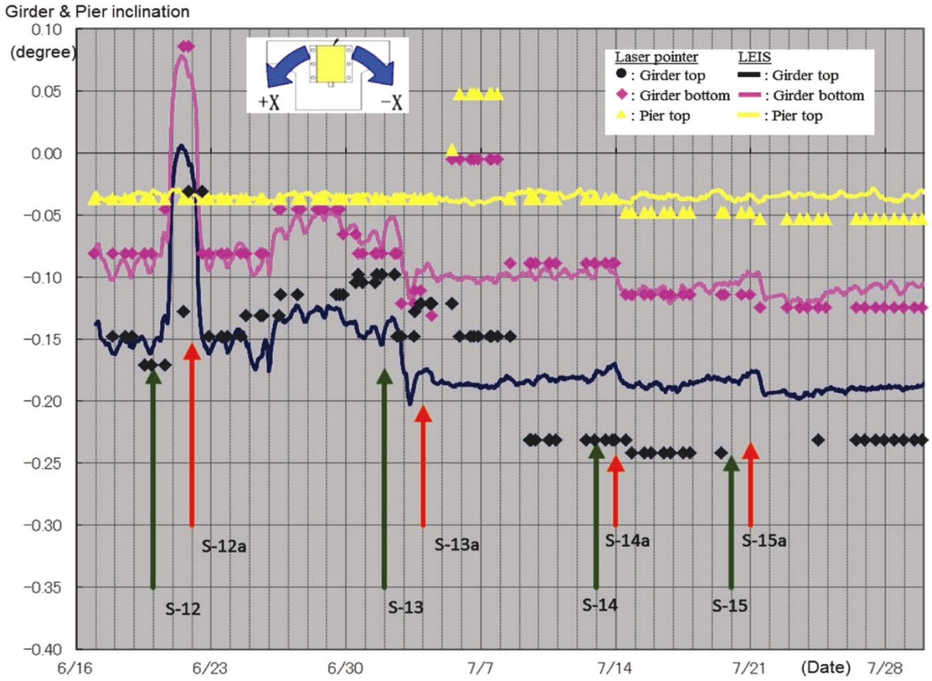


Figure 18. LEIS and laser pointer reading for longitudinal direction (*XZ*) at P220.

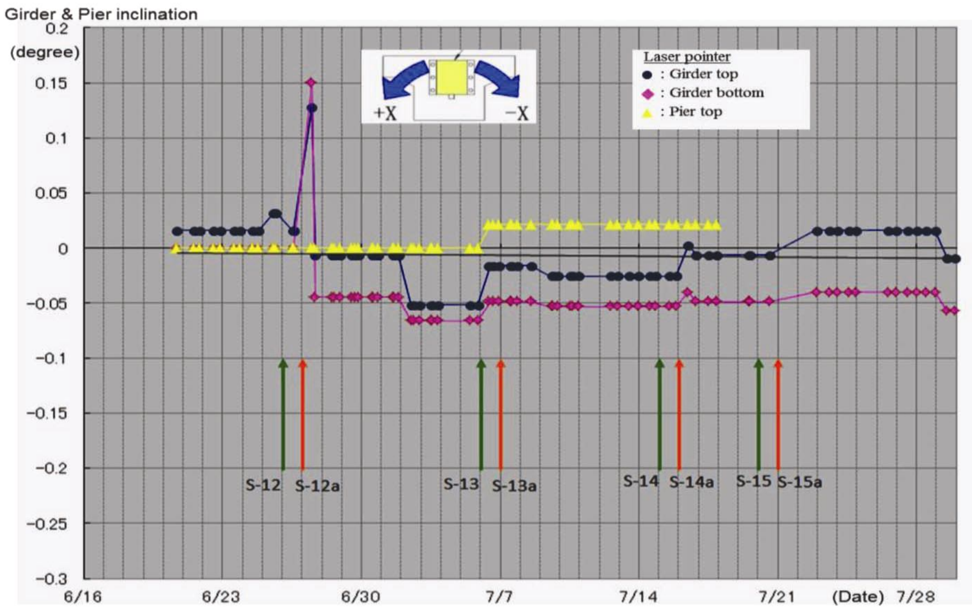


Figure 19. Laser pointer reading for longitudinal direction (*XZ*) at P221.

LEIS reading at transverse direction (*Y*) at Pier 220

Figure 16 shows the LEIS monitoring result θ_{YZ} of girder and pier in the transverse direction (*YZ* plane). Based on the design calculation, there is almost no inclination in *YZ* plane, but the inclination started and increased after S-10a casting. The need to measure girder and pier inclination in the *YZ* plane is that attention has to be paid to monitor the influence of the curvature ($R = 300$ m) of the bridge axis in the *XY* plane and excess loading to the bearing on the inner-side of curvature that is expected to increase stage by stage. The contractor's designer confirmed this deviation from the design is still tolerable and the construction proceeded with no counter measure. When the last segment S-15a was casted, the maximum

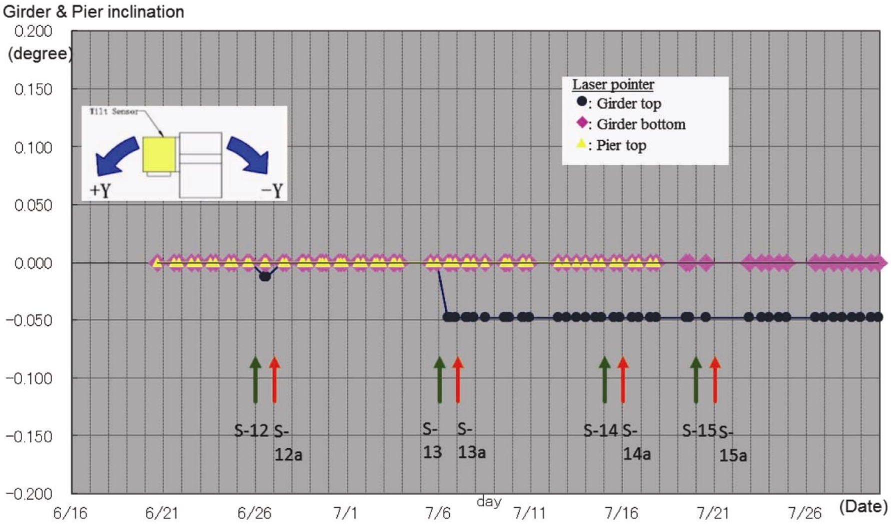


Figure 20. Laser pointer reading for transverse direction (*XY*) at P221.

girder inclination almost reached 0.15° as shown in Figure 16 and the bridge construction was just successfully completed without any problem.

Laser pointer reading at Pier 220

As explained in Figure 5, the location of laser pointer board was changed from far distance side to near side (bottom side) of the pier. Figure 17 shows the measurement details of inclination using laser pointers. If there is a girder inclination of 0.1°, a laser beam line inclines and its beam spot at about 10 m distance on display board at ground level moves by approximately 30 mm. Three laser pointers are installed near LEIS at P220 for the comparison of data.

Comparison of LEIS reading and laser pointer reading

Figure 18 shows LEIS reading and laser pointer reading after S-12a casting and both graphs show good correlation in spite of occasional problems at the site, such as touching of laser devices by workers, expiry of battery and movement of display board on the ground. LEIS readings also sometimes have errors due to micro computer problem and/or power break. Based on Figure 18, the difference in readings of both the instruments is within 0.05° and LEIS monitoring can be well replaced by laser pointer reading as a checking function of bridge girder inclination.

Laser pointer reading at Pier P221

There was no LEIS monitoring at P221 and laser pointer readings had the role entirely to check the girder and pier inclination (Figure 19). For longitudinal direction of the bridge, measured inclination by laser beam reading showed correct response based on the date of concrete casting and the tendency was the same as the one at P220. On the other hand, for transverse direction of the bridge, there is almost no movement as shown in Figure 20 and the behaviour is quite different from the one at P220, because P220 showed increased tendency for transverse inclination up to the end of construction with the value of 0.15°.

Conclusion and observations regarding OSV monitoring at Okla bridge

- The light emitting inclination sensor has captured the real behaviour of the bridge under construction in an unprecedented manner. Although when the data were corrupted due to technical problems or power break, all three sensors showed true structural behaviour of the bridge, including daily temperature effect. As the temperature control unit was embedded in LEIS sensor box, the working environment for the sensor was believed to be good, and therefore all structural temperature-effected movement seemed to be true. Visibility of light from rotating lamps was sufficient, although stronger light during daytime may be welcome.
- Use of laser pointers turned out to be a practical auxiliary method to trace angle change of a given structure. Although automatic data recording was not performed this time, the direct reading data of laser spots helped confirm the validity of the measurement results from LEIS. In addition, the laser pointers worked as sole monitoring performers for pier P221, revealing that the angle change happening to it was almost identical to what was happening to pier P220. Visual confirmation

of laser beam spots during daytime is difficult under strong sunlight. If data recording is absolutely necessary under such condition, some care must be taken so that beam spots can be recognized in a darkened box, for example.

- Appropriate threshold values to determine colour of light for LEIS cannot be determined before construction. The expected inclination for the bridge at an arbitrary stage of construction cannot be determined simply from the information available in a structural design stage. As the true behaviour is affected by several other factors, a trial period is required at the beginning of the monitoring project so that the information required to determine the appropriate threshold values can be obtained.
- The see-saw phenomenon of girder inclination longitudinally during the bridge segment casting at both sides was reasonable considering its behaviour in the *XZ* plane. However, the magnitude of angle change, the incremental inclination of the girder at each concrete casting was larger than expected from the elastic deformation of the trestle only, by a factor of 5 or more. It is anticipated that the slack (gap) in supporting structure caused this difference and pre-loading on supporting structure may be the solution to prevent such unexpected girder inclination.
- The inclination of girder and pier on transverse direction at P220 increased after S-9a casting dramatically towards the inside of horizontal curvature of bridge alignment. Because of inclination increase not only for the girder but for the pier, it is anticipated that all pier structures including raft foundation inclined based on ground compression. The inclination measured by laser pointers at P221 does not show this phenomenon. This may be because of pile foundation at P221 instead of raft foundation at P220.
- A trial run of the OSV monitoring showed a general trend of the structural movement during construction, thus enabling the selection of appropriate threshold values to define the colour scheme. This is one possible and practical approach to conduct the monitoring based on OSV. However, like in this case, the bridge construction was completed safely without any trouble throughout the construction sequences, despite the fact that inclination of much greater order than expected at the design stage was actually observed. It can therefore be concluded that continuous accumulation of data during construction and associated analysis of those data with respect to safety, must be performed so that the threshold values for the rational colour scheme could be determined with confidence prior to construction.

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