Geotechnical Design and Restoration Challenges of a Distressed Pier at Sultan Yusuf Bridge

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ABSTRACT

Yusuf Bridge is located near to the town of Teluk Intan which is about 160km North of Kuala Lumpur. The bridge was built in 1988 to cross the Perak River and link the Teluk Intan town and Setiawan town via the west coast road. The Perak River is the second longest river in Peninsular Malaysia, and is about 350m wide and up to 21m deep. The main bridge is a three-span structure supported by 2 piers in the Perak River. The rest of the viaducts on land are supported by piers on reinforced concrete piles. In 2017, one of the piers located at the riverbank on Teluk Intan side showed excessive movement which triggered an investigation. It was found that the bearing of the pier had experienced offset from its original centroid position and multiple distress cracks were identified around the pier head. The distress observed and continuous movement of the affected pier have caused an alarm to the Public Work Department (PWD) Malaysia as the bridge is heavily used by public and industrial transportation vehicles. Monitoring instruments which include manual and real-time monitoring were immediately installed after the distresses were found. Further to the monitoring, it was discovered that the pier together with the pile group had started to move actively toward the river. The pier had been observed to move more than 10mm per day towards the river which indicated a catastrophic failure to happen soon. This paper presents the attempts adopted in stopping the pier movement and discusses on the permanent restoration solution as well as the challenges faced during the restoration journey.

KEYWORDS: Underpinning, Bridge Restoration, Bored Pile, Micropile and Real Time Monitoring

1. Introduction

Sultan Yusuf Bridge is a 3-spans bridge of 95m + 160m + 95m long that was built in 1988 by Public Works Department (PWD) Malaysia to cross Perak River in Teluk Intan. This long span bridge was considered as one of the longest bridges in Peninsular Malaysia when it was built 30 years ago in the 80s. The bridge provides a permanent navigation clearance of 12m above high-water level. The 3 main spans consist of segmental prestressed box-girders supported by 2 piers located in the river where they are founded on large diameter steel piles of 90m length. The connecting viaducts on land consist of precast prestressed concrete beams supported on reinforced concrete piers spaced at 33.5m c/c and founded on huge pile group of reinforced concrete piles. Figure 1 below shows the longitudinal section of Sultan Yusuf Bridge.

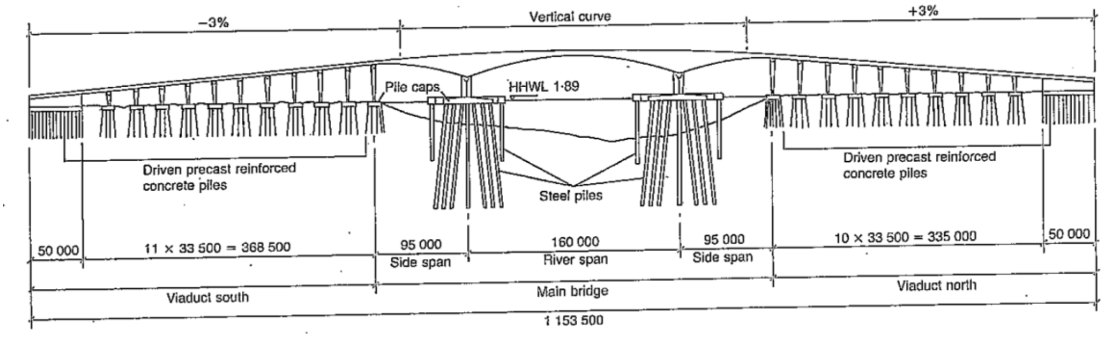

Figure 1. Longitudinal Section of Sultan Yusuf Bridge

Pier 11 and Pier 14 are piers constructed next to the riverbank. Over the past 30 years, Pier 11 which is situated on the riverbank of Teluk Intan (South) side was identified to be badly eroded during a visual inspection in July 2017. The pier was observed to have been partly submerged in the river and part of the pile cap was exposed. Some major distresses were observed at the crosshead, and the pot bearing had been identified to be severely damaged. Other distress observed is the significant drop of the viaduct deck (about 100mm) at the connection between bridge box girder and land viaduct span.

2. Observed Distress and Temporary Rectifications

2.1. Distresses and Signs

A significant 100mm drop of the viaduct deck, which was initially detected in July 2017 had triggered a detailed inspection of Pier 11. Further inspection of Pier 11 was carried out in August 2017, which provided an observation that the original pot bearing was fully damaged with the center support of the deck had shifted significantly to one side. The pot bearings beneath both viaduct span and box girder span were identified to be completely driven out from the original position as shown in Figure 2. The pier had been observed to be tilted and moved excessively toward the river direction, which led to the observation of severe damage and cracks on the pier column and pier crosshead beam. Figure 3 indicates an obvious drop of 100mm at the bridge and land viaduct connection. Figure 4 shows an aerial view of the dislodged position of Pier 11. Part of the pile cap was observed to be exposed which was likely due to the river erosion over the duration of 30 years. The loss of the soil passive resistance in front of the pile group (at the riverbank) would likely be one of the triggers to the movement.

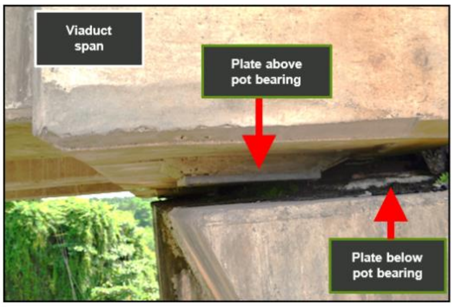

Figure 2. Pot Bearing Location

Figure 3. 100mm Drop in Level

Figure 4. Aerial View of Pier 11 offset from Center Line

During the inspection, Pier 11 was still moving aggressively towards the river which demanded an immediate rectification measure. Instrumentation monitoring that consisted of prism and real-time tiltmeter was proposed and installed immediately. In a few weeks, the monitoring results showed about 10mm of lateral movement per day. This is quite an alarming trend and has attracted serious attention from the Public Work Department (PWD). Instruction to close the bridge had been made by the local council with recommendation from PWD. Consultants and contractors were asked to look into the remedial measures and carry out immediate actions to slow down the movement. With that high movement rate, Sultan Yusuf Bridge was feared to experience collapse in the coming months which would be a national catastrophic.

2.2. Temporary Rectifications

Every hour was crucial as the consultant and contractor worked around the clock to come out with a feasible solution to stop the rapid movement of Pier 11. Although the bridge had been closed to public, collapse of the bridge would be a national disaster. Many ideas were thrown into the discussion and finally, several sequence of temporary stabilization measures were decided.

The first step taken was to install a row of sheet piles in between Pier 10 and Pier 11. The sheet piles were driven to 24m depth. The sheet piles at the center were driven in 6m connections due to the height limitation. The objective is to reduce the driving force of the soft ground towards the river and stabilize the ground surrounding Pier 11. The typical layout is shown in Figure 5.

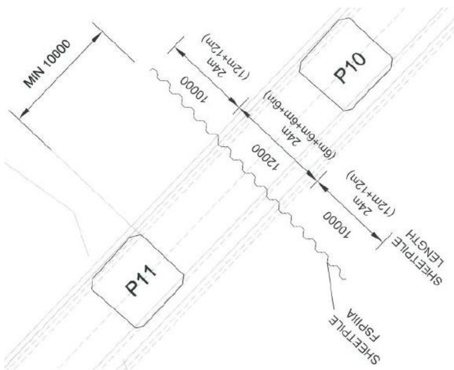

Figure 5. Layout Plan of the Temporary Remedial Measure using Sheet Piles

The next step was to temporarily stabilize the riverbank and create passive resistance to Pier 11. This was done by using sandbags and rock filling at the riverbank in front of Pier 11. Analysis had been carried out on two (2) conditions; Condition 1- original eroded riverbank & Condition 2 - riverbank stabilized by sand and rock fill. The analysis results showed an increase of factor of safety (FOS) from 1.2 to 1.6. Illustration of the proposed filling is given in Figure 6.

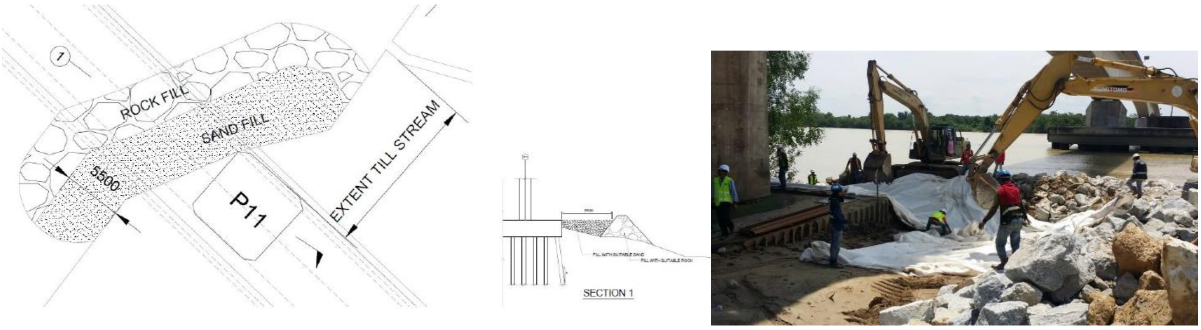

Figure 6. Sandbags and Rock Filling

However, the filling using rock fill and sandbags at site were not as ideal as the planning. Most of the sandbags and rock fill were washed away during the execution and the contractor was unable to obtain sufficient supplies due to the short notices. The pier movement was still moving at an alarming rate. Given the critical moment, the consultants proposed a solution of tying Pier 11 to multiple adjacent piers (Piers 8,9 & 10) using wire rope and chain block. Analysis was carried out to calculate the rope size and length. Figure 7 shows the layout and elevation of the wire rope solution.

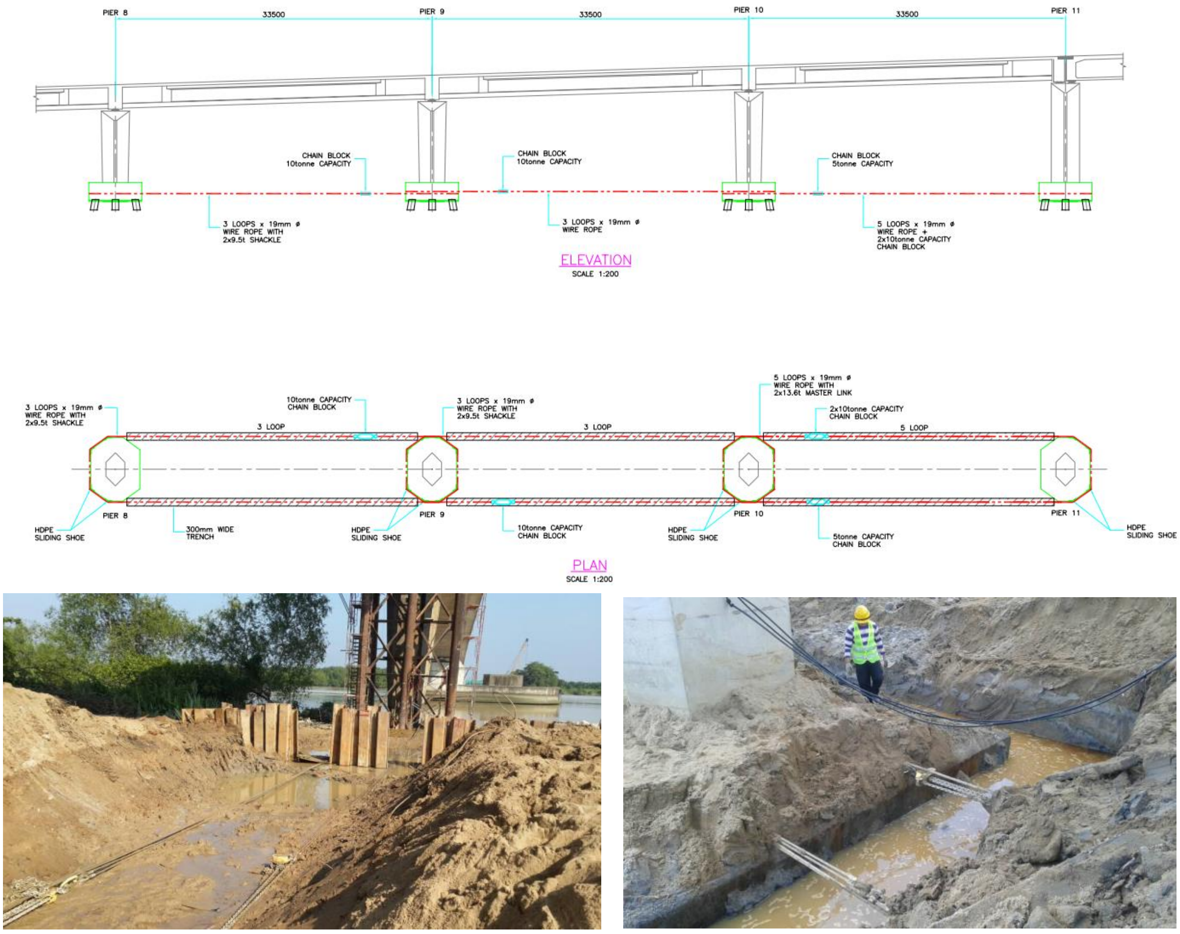

Figure 7. Layout and Elevation of Tying Pier 11 with Wire Rope

Concurrently, a temporary steel frame support was proposed and carried out to support the crosshead and bridge deck. This approach was to assist in supporting the deck as the pot bearing had been completely damaged and Pier 11 was still moving actively. Figure 8 shows the temporary steel support.

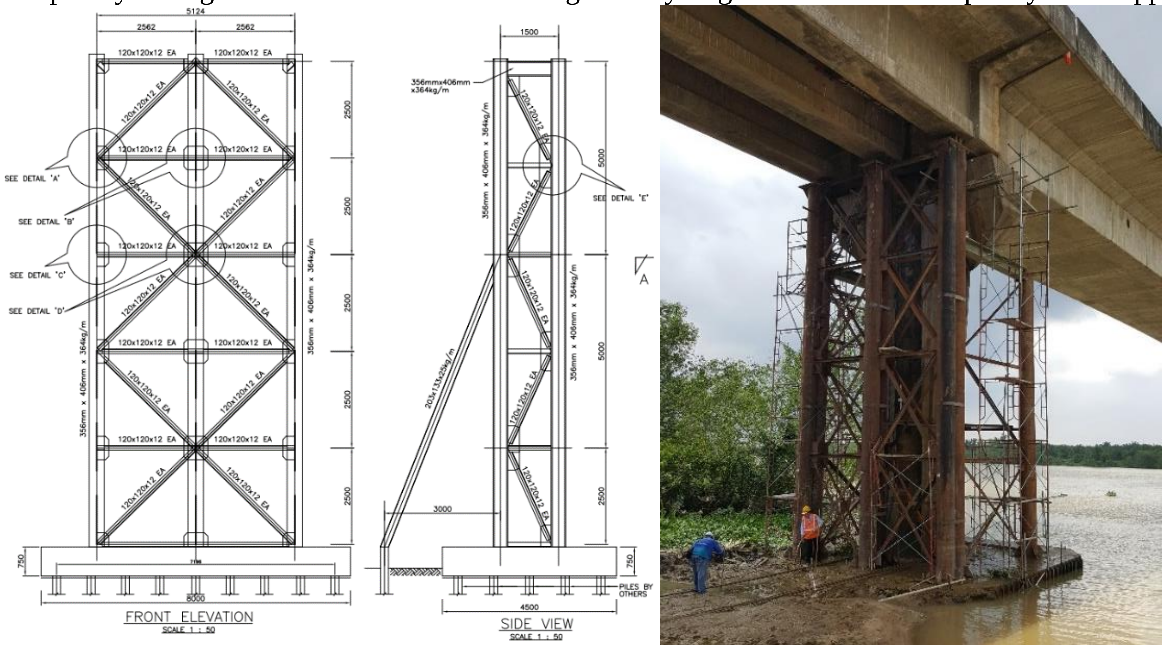

Figure 8. Temporary Steel Frame to support the Crosshead

With all these temporary remedial proposals in place, the contractor had worked around the clock and successfully completed the temporary rectifications in a duration no more than a month. These remedial measures had successfully impede the movement of Pier 11. Nevertheless, the monitoring readings still showed signs of instability where permanent rectification solution was required.

3. Monitoring Results and Interpretation

Instrumentation monitoring had been proposed and installed almost immediately after the distresses were identified. Real-time monitoring and manual survey monitoring were carried out to monitor closely the Pier 11 condition while the consultants were working on the temporary remedial measures. The real-time monitoring installed were displacement tranducers, tiltmeters and crack displacement transducers, while prisms were used for the manual survey using total station. The positions of the instrumentation are shown in Figure 9. During the critical moment, all the readings were taken daily.

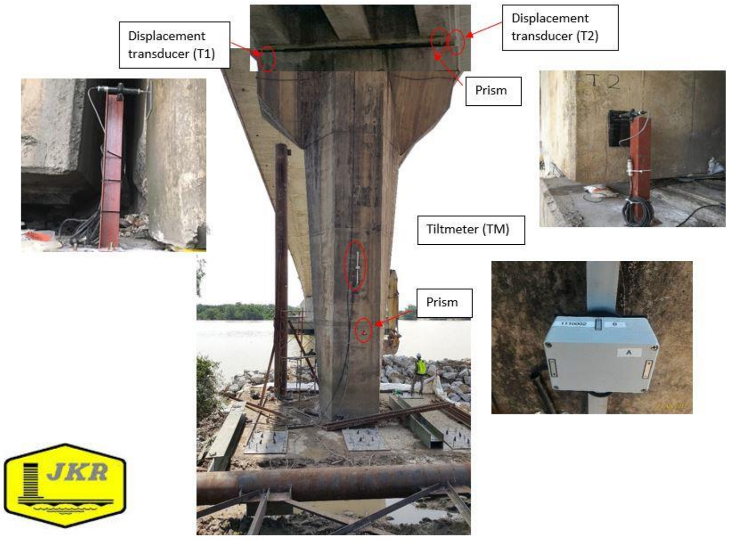

Figure 9. Position of Instrumentation Monitoring at Pier 11

3.1. Monitoring at Critical Moment (Before Stabilization Measures)

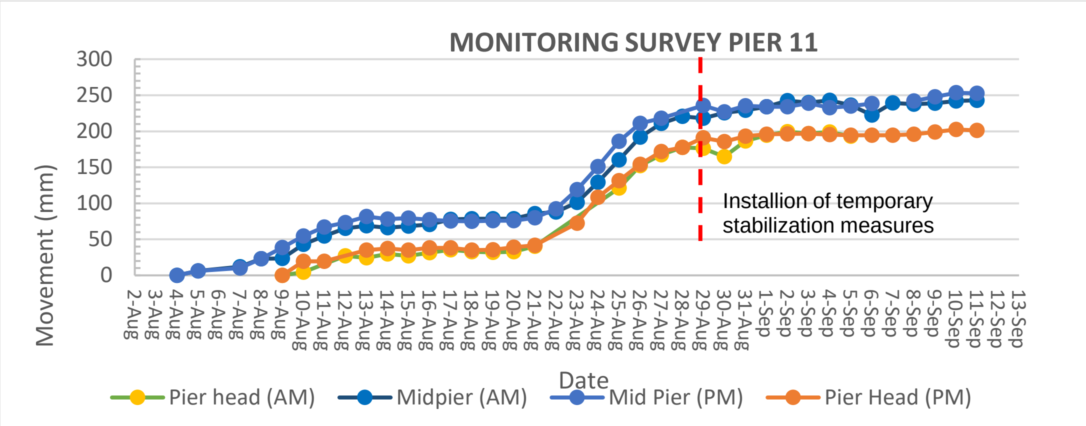

Figure 10. Manual Monitoring Data of Pier 11

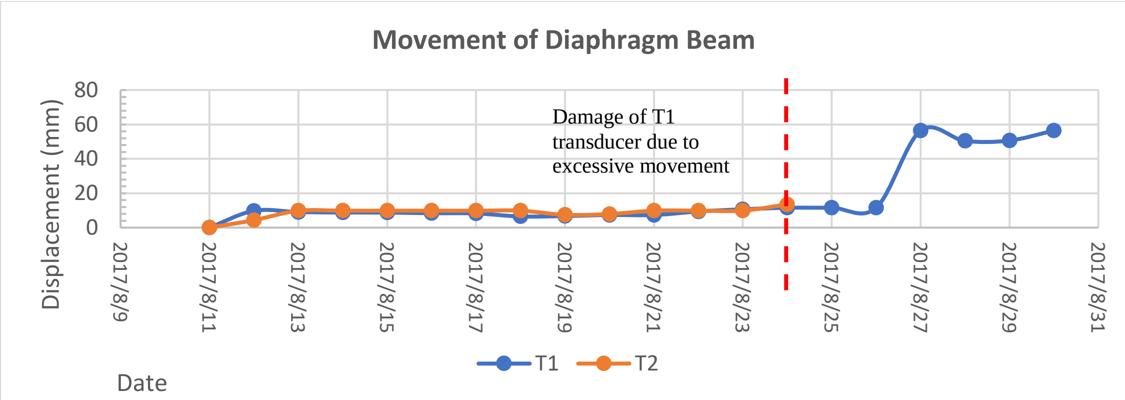

Figure 11. Real-Time Monitoring Data of Diaphragm Beam (Pier 11)

Both the manual survey monitoring and real-time monitoring showed an active movement of Pier 11 towards the river. Manual readings taken from August 2017 to September 2017 (Figure 10) showed pier displacement at rate of 20mm/day within the final week of August 2017 while the real-time monitoring (Figure 11) at the pier head/diaphragm beam showed drastic increase of movement at the end of August 2017. The transducer T1 was found damaged due to the excessive movement of the diaphragm beam as shown in Figure 12. Once the temporary stabilization measures were in place in September 2017, it can be seen a rapid decreasing trend of pier movement. Due to the huge inconvenience of the bridge closure to the public, PWD and local council had asked the consultants to look into the possibility of opening the bridge in parallel to construction of permanent rectification. Several discussions and assessments had taken placed among the consultants, and decision had been made to open the bridge to light vehicles on 30 December 2017.

Figure 12. Damage of the Real-Time Transducer due to Excessive Movement

3.2. Monitoring during Permanent Restoration

One (1) no of inclinometer was installed in front of Pier 11 for ground movement monitoring. Inclinometer is used to monitor the ground movement with depth. Readings were taken daily. The location of inclinometer is shown in Figure 13.

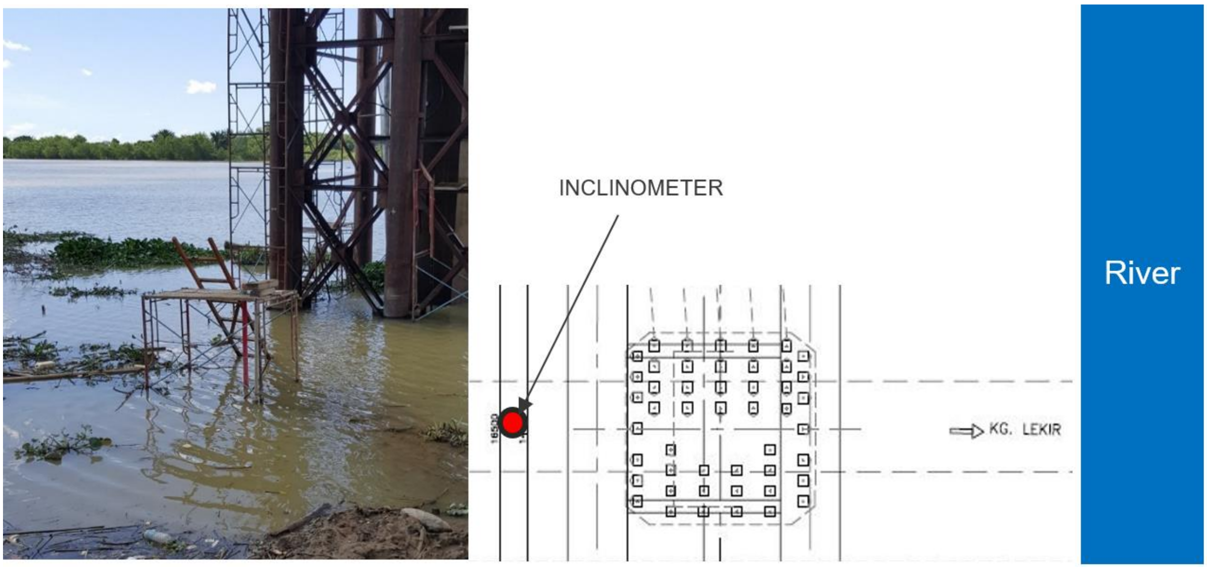

Figure 13. Location of Inclinometer in Reference to Pier 11

Figure 14 shows the total ground movement of 187mm towards the river over the duration of 8 months starting from 20 October 2017 where the maximum movement was recorded within the top 3m depth and the movement reduced with depth. For a duration of 6 months when the bridge was reopened to light traffic until the completion of the permanent support structure (end of June 2018), the ground was recorded moving 137mm towards the river.

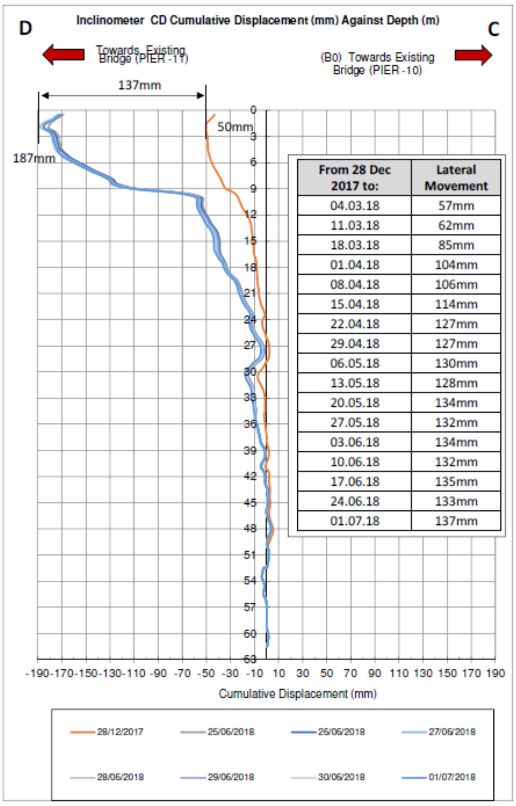

Figure 14. Inclinometer Readings

The manual monitoring using total station on Pier 11 body was carried out daily. The Public Work Department requested a daily update on the pier condition after the bridge had reopened to the light vehicles on 30 December 2017. While the permanent restoration design and works were in progress, Pier 11 condition had been closely monitored on the lateral movement and settlement.

Figure 15 shows that Pier 11 had experienced progressive movement towards the Perak River. Interestingly, the movement had been gradual at a rate of about 0.6mm/day since the bridge reopened until early March 2018 where the permanent restoration foundation work commenced. During the restoration works, the pier movement rate had increased to 3.8mm/day which was an alarming rate. An emergency meeting was called, and consultant had proposed an adjustment to the permanent design. Further monitoring showed that the movement had stabilized, and the permanent restoration work continued as planned. A total movement of 108mm was recorded for the duration of 6 months.

In terms of settlement, Pier 11 was observed to experience quite an active settlement rate. As shown in Figure 16, high settlement was recorded in early January 2018 where the bridge was reopened to light vehicles and the bored pile foundation was in progress. In February 2018, the settlement rate had reduced to quite a nominal rate of 0.3mm/day before the rate increased to 1.1mm/day in March 2018. This is likely due to the construction work of permanent foundation for Pier 11. The settlement rate is seen to reduce to a nominal value of 0.1mm/day from April 2017 onwards.

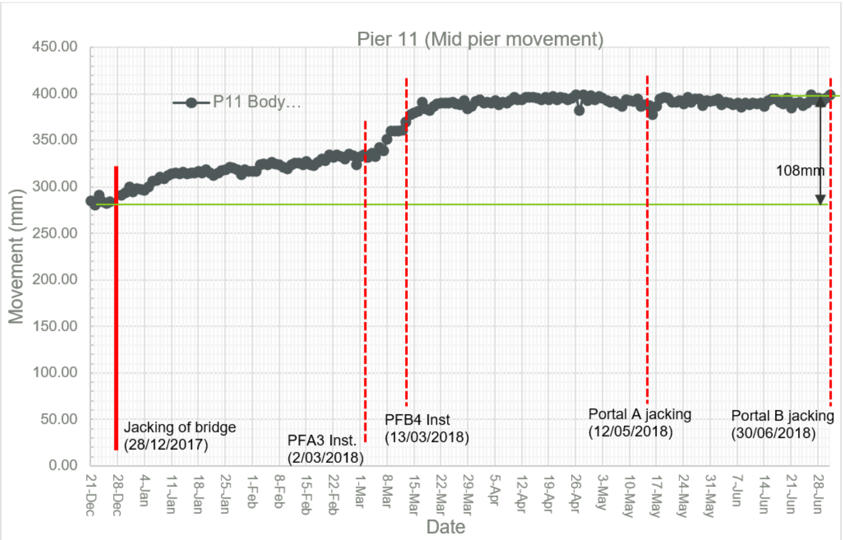

Figure 15. Pier Lateral Movement Graph

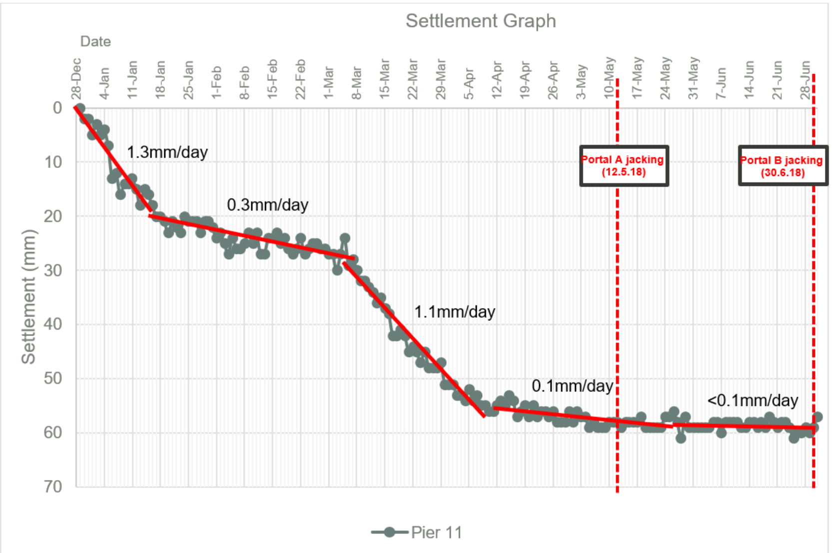

Figure 16. Pier Settlement Graph

4. Permanent Restoration

4.1. Proposed Permanent Underpinning Structure

Pier 11 had been identified to experience excessive movement in August 2017. The Sultan Yusuf Bridge was closed entirely to any vehicles. Instrumentation monitoring was carried out, and temporary stabilization approaches were proposed and executed within a short duration of less than a month with the cooperation among the consultants, contractor, and authority. The bridge was decided to reopen to light vehicles on 30 December 2017 while the consultants continued to work on the permanent solutions.

The existing pile group consists of 50 numbers of reinforced concrete piles sized 385mm x 385mm. All the piles were reported being driven to 36m (unset). Based on the measurement of the pot bearing center line, it was assumed that Pier 11 had moved as much as 1.2m. Analysis had been carried out to establish the existing condition of the pile group. The analysis showed that about 50% of the existing piles were beyond the ultimate state condition and the pier was relying on the capacity of the balance 50%. Figure 17 shows the analysis output.

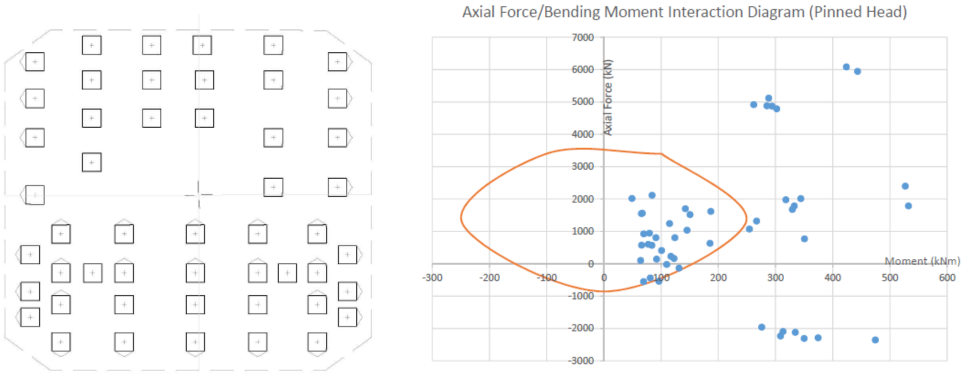

Figure 17. Assessment of the Existing Pile Group

Decision had been made that the existing pile group shall be omitted from the design considering the uncertainty and damage to the pile group. The new design consists of two numbers of reinforced concrete portal frames constructed on both sides of the existing Pier 11 where Portal A (front) to support viaduct span while Portal B (back) to support box girder span. Both the portals were connected by tie beams and supported by 4 numbers of 1.5m diameter bored pile and 16 numbers of 300mm diameter micropiles. Bored piles were installed to a depth of 50m while micropiles were installed to a depth of 92m as shown in Figure 18. The portal frames were reinforced by bracing of 500mm diameter steel pipe sections.

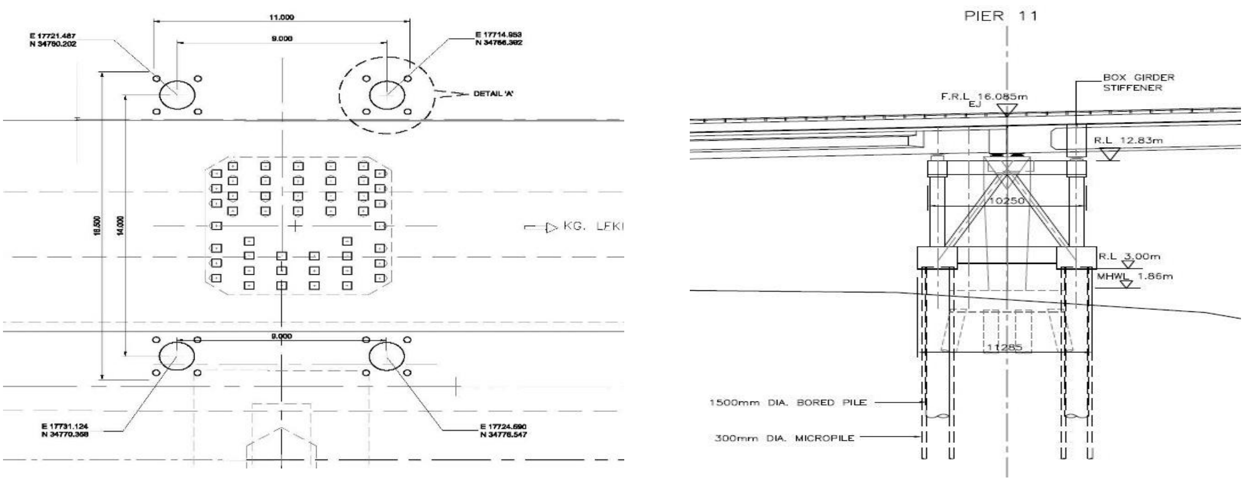

Figure 18. Layout and Section of Permanent Restoration

4.2. Analysis and Design

Prior to the design, 2 nos of additional boreholes were carried out to 90m depth to obtain the subsoil profiles and soil parameters. The interpretation of the soil stratification and parameters is shown in Figure 19.

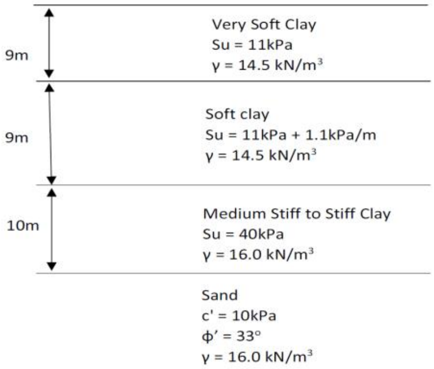

Figure 19. Soil Layers and Parameters

Analysis was carried out by considering the erosion of the riverbank. The bathymetric survey carried out showed that the slope beneath Pier 11 was badly eroded with steep inclination. The slope stability analysis carried out indicated a minimum factor of safety (FOS) of 1.20 which is lower than the allowable FOS of 1.30. This condition would likely induce lateral squeeze onto the new proposed foundation. Hence, the additional lateral squeeze force was calculated using Plaxis 2D finite element modelling where the output is shown in Figure 20. The analysis result was also cross-checked with the empirical approach based on Debeer & Walley (1972) method where an additional moment of 607kNm was calculated.

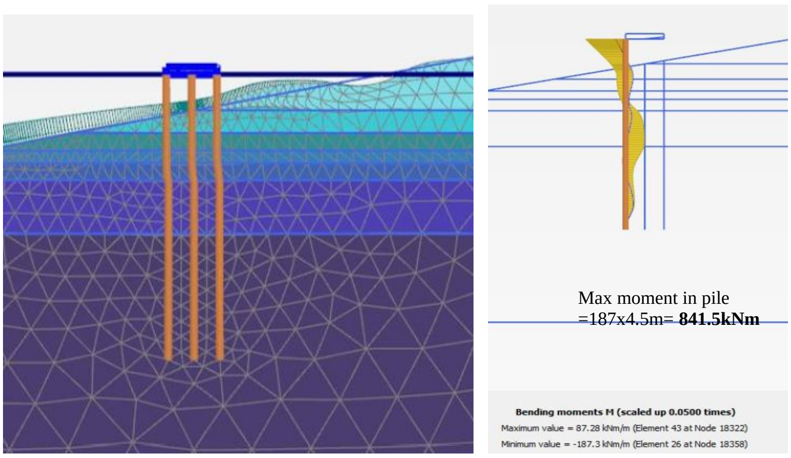

Figure 20. Finite Element Analysis Result

Both the finite element analysis and empirical approach produced additional moments, i.e. 841.5kNm and 607kNm respectively, due to the effect of lateral squeeze. A final value of 850kNm was adopted for the bending moment design. The foundation was then designed accordingly. The summary of the remedial foundation is given in Table 1.

Table 1. Remedial Foundation Piling Details

Bored Pile			Micropile with Permanent Casing			
Diameter (m)	Length (m)	Working Load (kN)	Diameter (m)	Length (m)	Working Load (kN)	API Size (mm)
1.5	50	3800	0.3	92	1100	177.8 x 10.36

5. Discussion of Challenges and Issues

During the course of Pier 11 rectification, many issues and obstruction were encountered that challenged the consultants and contractor involved. The consultants and contractor together with the authority had worked tirelessly to address the critical movement of Pier 11 which may lead to a catastrophic collapse to endanger the life of the road users. Some of the key challenges are discussed as below:

Temporary Stabilization within Short Period of Time

When Pier 11 was identified to experience distress and excessive movement, consultants were given a very small time window to work on the theory and provide a workable solution. It was a stressful situation when the proposed stabilization approach using rock fill was not effective. Contractor was unable to obtain sufficient amount of rock fill and sandbags due to the short notice. Finally, an alternative using wire rope tied to the adjacent piers and removal of some earth to relieve the soil load of the movement has successfully reduced the pier 11 movement.

Effect of Permanent Restoration Work on the Existing Pier 11

The permanent design consisted of large diameter bored piles which required huge piling machinery. Pier 11 was located at the riverbank where there was no proper working platform level. Contractor was advised to construct a temporary steel platform for the rectification work in order to minimize any transfer of load which would possibly aggravate the existing Pier 11. The temporary steel platform consisted of H-piles driven to 80m depth. During the installation, monitoring readings showed increase of Pier 11 lateral movement. This indicated that Pier 11 was very sensitive to the surrounding activities. Contractor had been briefed on this and the temporary platform had been completed delicately. Due to the sensitivity of the existing Pier 11, the bored piles installation was carried out using the Reserved Circulation Drilling (RCD) method to reduce the vibration impact. The initial foundation design only consisted of 4 nos of bored pile installed to a depth of 93m. Permanent steel casing was originally proposed for the top 24m, however, it can only penetrate to 22m depth. The installation proceeded with polymer as the stabilization fluid. At the depth of 37m, collapse of the hole occurred during boring. The sample retrieved from the boring indicated fine and white sand material. Several attempts were carried out to bore through but collapse of the hole kept happening between depths of 37m to 39m. It was likely that 2m thick of sand lenses were present at the depth of 37m. The contractor decided to backfill the hole and re-bore with permanent casing all the way using the vibro method. As the casing being vibrated deeper into the soil, Pier 11 was observed to settle drastically at a rate of 10mm/day. This settlement trend was alarming. The casing installation was stopped at the depth of 46.5m, further boring using stabilization fluid could not stop the collapse of hole at 50m depth. Hence, the consultants decided to terminate all bored piles at 50m depth and improvised with micropiles to support the balance load. 4 nos of micropile were paired with each bored pile. Micropiles with permanent casing were designed to a length of 92m. The bored pile had been used as a guide for the micropile installation to ensure the straightness. The micropile’s shaft friction within the bored pile length was ignored in this design due to the close spacing.

Opening the Bridge to Road Users during Restoration Works

Sultan Yusuf Bridge was only fully closed to the public for less than 4 months. The bridge was announced to be closed to any road users on 2 September 2017 when Pier 11 was assessed being at critical condition. The bridge was opened to light vehicles on 30 December 2017. Sultan Yusuf Bridge is the main link between Teluk Intan town and Manjung town where the bridge is heavily used to connect to the coast. The bridge closure had caused a huge inconvenience to the road users where they had to use alternative route with a longer journey time. After the temporary stabilization solution had successfully decreased the movement of Pier 11, the consultants were asked to consider for re-opening the bridge to the public during the permanent restoration works. As a result, assessment had been carried out on the existing pile group. Decision had been made to open the bridge to only light vehicles with conditions that temporary steel frame structures needed to be erected to provide additional support to Pier 11 and instrumentation with real-time to be installed for close monitoring of the pier condition.

6. Completion of Permanent Restoration Design of Pier 11

The construction of new Pier 11 started in December 2017 where the installation of bored piles experienced some hiccup that led to the improvisation of the foundation design. Full swing of the construction commenced from February 2018 until the superstructure (RC portal frames) was completed in April 2018. The transfer of the bridge load to the two permanent portals was carried out at 1 month apart to ensure a smooth transferred without affecting the public road users. The bridge load transfer to Portal A carried out on 12 May 2018 while jacking of Portal B was completed on 30 June 2018 which signified the successful completion of the permanent restoration work. The existing pier was demolished. Many unpredictable obstacles were faced and solved by the consultants, contractors and authority during the course of the restoration work which is a piece of engineering achievement. The success of this restoration work in a tight deadline and putting public safety as priority sees a mutually cooperative effort and high level of commitments among the consultants, contractors and Public Works Department personnel. Figure 21 showed the completed restoration of Pier 11 with new structure and foundation.

Figure 21. Completed Restoration of Pier 11

7. Conclusions

The completion of the new Pier 11 restoration represents a great effort and cooperation among the consultants, contractors and Public Work Department. The instability experienced by Pier 11 due to the riverbank erosion was in the critical state of collapse. Quick efforts were carried out by all parties to stabilize the pier and avoid the possibility of catastrophic collapse. The restoration work involved underpinning and re-construction of a new support for Pier 11. The re-construction was carried out while the bridge was opened to light vehicles as closing the bridge for a long time would be a major inconvenience to the public. The restoration and re-construction works were successfully completed in July 2018 in the timeframe of less than 1 year.

8. Acknowledgement

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