

Settlement Monitoring of Georehabilitation Solution at Bridge and Culvert Approaches using Polyurethane Foam Injection System

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Abstract

Differential settlement at transition approaches has caused major problems to road users whereby the kink at the approach section could affect the riding ability and discomfort. The issues relating to differential settlement is due to high dynamic impact from heavy traffic loads, consolidation settlement of the foundation soil, poor compaction and migration of the earth fill underneath the voids of the piled embankment or bridge abutment created from global settlement of the surrounding area. The proposed solution mostly resorts to the reconstruction of the approaches, thereby requires excavation and construction of transition or approach slabs. In this paper, an alternative solution using polyurethane (PU) foam injection system was introduced to reduce the effect of differential settlement at the approach bridges and culverts, thus provide minimal disruption to traffic users and operations. The objectives of the proposed georehabilitation solution are i) to reduce the effect of soil migration and settlement underneath the transition section; and ii) to stabilize the ground by increasing the bearing resistance without increasing the existing overburden pressure to the foundation soil. Settlement monitoring was conducted to ensure that the solution performs to the required specification. This paper will provide results for two (2) locations at FT005, Kuala Selangor Federal Road, specifically, the Kuala Selangor bridge approach and the Sungai Gulang-Gulang culvert approach. The results showed that there is significant reduction in the differential settlement of the approach sections, hence the need to resurface or regulate the pavement for routine maintenance is needed.

Keywords: Bridge Approach, Culvert Approach, Differential Settlement, Georehabilitation, Polyurethane Foam

1. Introduction

The Federal Route FT005 is one of the three north-south oriented backbone federal road running along west coast of Peninsular Malaysia. The 655.85 km federal highway runs from Skudai, Johor and ends at Jelapang, Perak and FT005 is also the shortest among the three backbone federal highways. This federal route FT005 starts from Skudai, Johor and at Sepang, where the Federal Route 005 is rerouted to Jalan Morib. Then the Federal Route FT005 is diverted to Jalan Kapar and forms a part of the Klang – Teluk Intan Road FT005. In 1970, the Kuala Selangor bridge was proposed to link between Federal Route FT05 from Klang to Teluk Intan. (Wikipedia, 2022)

The settlement after post-construction has always been a challenge in the construction of road embankments on soft ground deposits. The ground settlement occurs due to the volume change of soft soil as the excess pore water pressure dissipates when the ground was loaded to strengthen the foundation of the building and pavement. In Malaysia, there are many cases of differential settlement occurring at transition bridge and culvert approaches, especially on soft soil deposits. The abutment approach on the viaduct section of Federal Route FT05 just right after Sungai Selangor and the box culvert approach on the road section of Federal Route FT05 just right after the intersection of Jalan Sungai Gulang-Gulang are the selected area for the proposed georehabilitation solution using polyurethane (PU) foam injection system. This problem has occurred numerously; thus the existing solution is to regulate and resurface the settled section with additional premix to realign vertically from the bridge and culvert approaches with the transition earth fill embankment. Figure 1 and Figure 2 illustrates the overview of the Kuala Selangor Bridge approach and the intersection of Jalan Sungai Gulang-Gulang, respectively.

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Figure 1. Overview of the Kuala Selangor Bridge approach.



Figure 2. Overview of the Jalan Sungai Gulang-Gulang culvert approach intersection.

2. Site Geomorphology and Geology

Generally, the site topography at the Kuala Selangor Bridge consists of flat terrain surrounded by commercial building, housing areas and the most important things is swampy areas near the bridge approached. The swampy areas surrounded all over the bridge will be the main factor that contribute to the settlement process of the rapid underlain of the road on the viaduct section. The geological formation found in most of the site location situated in Kuala Selangor areas is dominated by quaternary formation which consists of marine and continental deposits such as clay, silt, sand and minor gravel. Based on the geological map shown in Figure 3a and Figure 3b, this study area consists of fine soil particles especially silt and clay lie beneath the subsoil of the site location. (Nedal *et. al.*, 2007)

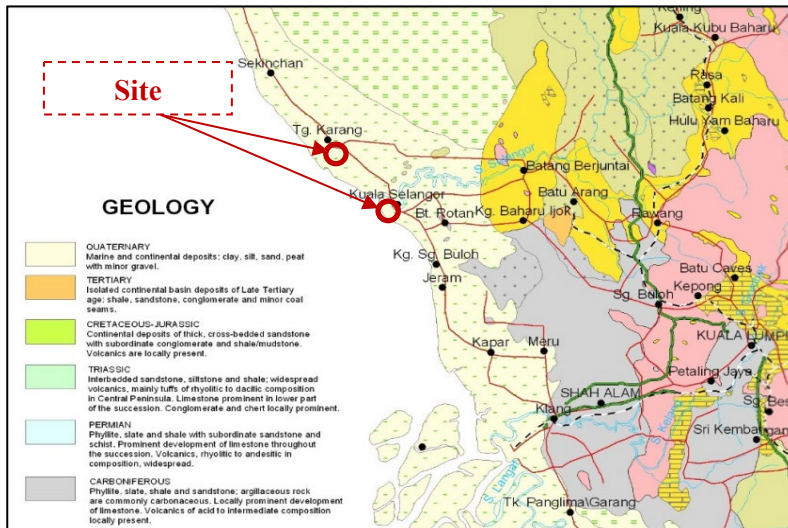


Figure 3(a). Geological formation of the site location at Kuala Selangor, Selangor. (JMG, 2000)

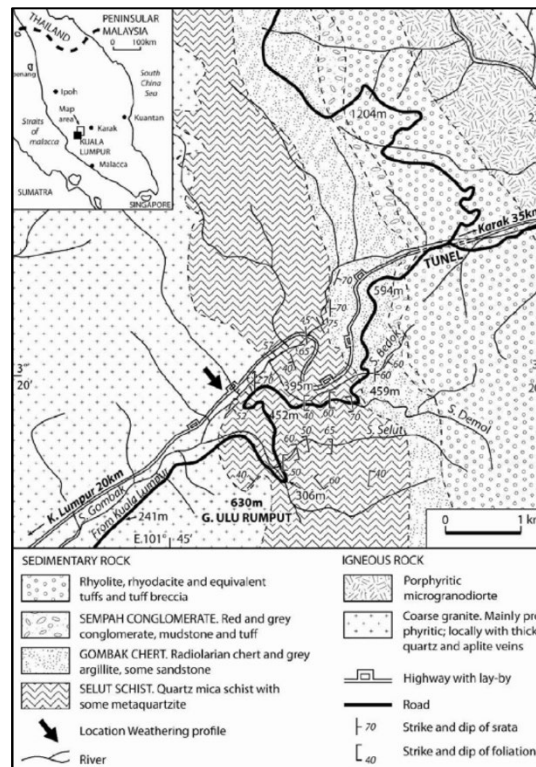


Figure 3(b). Geological interpretation of rock properties at Kuala Selangor, Selangor. (JMG, 2000)

2.1 Section 481.7, Federal Route FT05 (Sultan Salahuddin Abdul Aziz Bridge)

The site topography at the Sultan Salahuddin Abdul Aziz (SSAA) Bridge or known as Kuala Selangor Bridge consists of flat terrain surrounded by commercial building, housing areas and the most important thing is swampy near the bridge approach as shown in Figure 4. The swampy areas surrounded all over the bridge is

one of the main factor that contributes to the settlement process of the transition section underlain the road on the viaduct section (Zainuddin *et. al.*, 2021).

2.2 Section 491.8, Federal Route FT05 (Sg. Gulang-Gulang Box Culvert)

The topography at the Jalan Sungai Gulang-Gulang consists of flat terrain surrounded by commercial building, housing areas and agricultural land as shown in Figure 5. The settlement occurred on the left and right side of the box culvert causing undulation and discomfort to the traffic users.



(a)



(b)

Figure 4. Site location of Kuala Selangor Bridge (a) Plan view of the bridge; and (b) Photo of the bridge from west bound to Klang view.



(a)



(b)

Figure 5. Site location of a box culvert at Sg. Gulang-Gulang (a) Plan view of box culvert; and (b) View the carriageway from Klang to Sabak Bernam.

3. Georehabilitation Solution using Polyurethane (PU) Foam Injection System

The polyurethane (PU) foam injection system was extensively explained by Mohamed Jais *et al.* (2015a) (2015b). Lat *et al.* (2020), Mohamed Jais (2017) and Lat *et al.* (2015). PU foam/resin is one of the alternative lightweight material which is widely used in the ground improvement work. The function of lightweight material in highway construction is to improve the poor foundation (soft soil) without imposing any additional loading on the existing foundation and at the same time, the increases the soil bearing capacity.

PU foam/resin is a polymeric material and has a variety of physical and chemical properties. PU foam/resin is a cellular solid PU polymer like honeycomb structure that is designed to obtain the desired properties (Gladysz *et. al.*, 2021). There are two (2) types of polyurethane foam/resin; namely, hydrophobic and hydrophilic polyurethanes. Hydrophilic polyurethane reacts and absorbs water before it expands up to five (5) to seven (7) times to form flexible foam or gel. Whereas, hydrophobic can expands six (6) to 20 times from its liquid volume,

thus naturally repels water and stabilises the surrounding soil. This behaviour shows that hydrophobic polyurethane is more suitable for ground repair and remediation applications (Jais, 2017). According to Mohamed Jais (2015b) and Lat *et al.* (2020), polyurethane (PU) foam is a reaction of two compounds, namely polyols (-OH) and isocyanates (-NCO) during polymerization of polyurethane. The reaction between polyol and isocyanate is as follows:

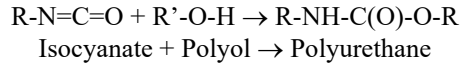


Figure 6 shows the example of the microstructure of PU foam/resin observed by Lat *et al.* (2021). Table 1 presents the PU foam properties used for the design and application in the georehabilitation solution.

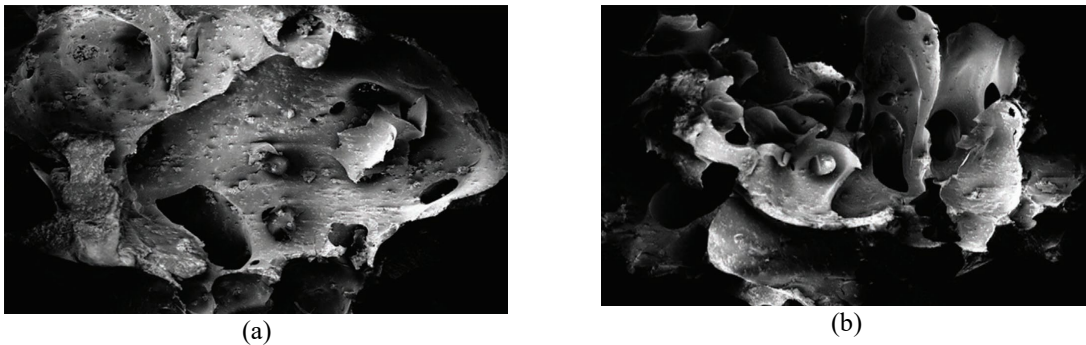


Figure 6. The image of microstructure by using electron microscope (a) PU foam; and (b) Intrusion of PU foam into laterite soil (Lat *et. al.*, 2021)

Table 1. Design properties of the polyurethane foam/resin (Jais, 2017)

Description	Value	Unit
Unit weight of the polyurethane foam/resin, γ	3	kN/m ³
Stiffness modulus, E	15,000	kN/m ²
Poisson's ratio, ν	0.3	
Compressive strength, σ	2.2	MPa
Permeability, k	1×10^{-12}	m/s

3.2 Georehabilitation Solution

The concepts of typical implementation of PU foam injection system at bridge and culvert approach are shown in Figure 7. The injection points were arranged from 1 m to 2 m spacing. The curing time of the expansion foam is about fifteen (15) minutes after each injection. The packer was dismantled, and the holes were grouted with a suitable material. Any diffused and spilt PU needs to be removed before the crack repair can be executed. This stage is executed to plug the voids beneath the culvert or abutment structure creating a lightweight curtain wall, thus preventing the adjacent compacted earthfill material migrating into the voids. This will reduce the migration of the compacted soil into the void spaces, hence reduces the rate of differential settlement at the approach section.

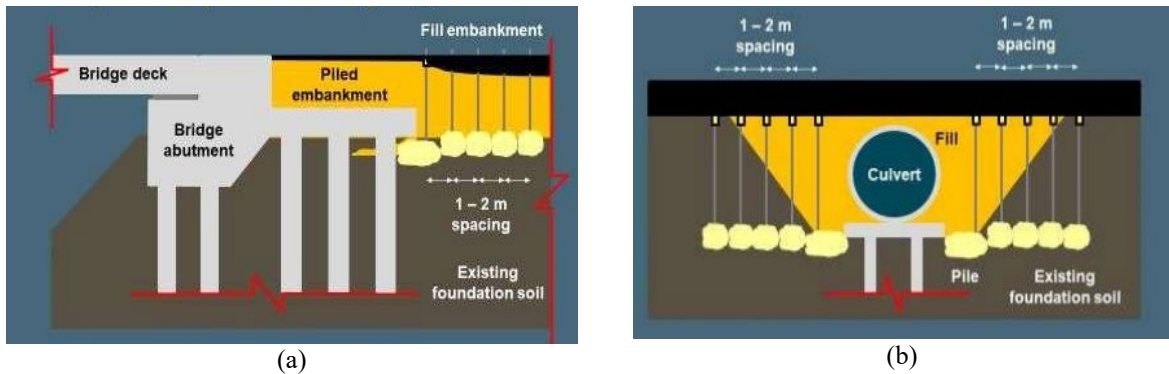


Figure 7. The rehabilitation technique applying polyurethane foam/resin at (a) bridge and (b) culvert approaches (Courtesy of Geocon (M) Sdn. Bhd.).

3.3 Configuration of the PU Foam Injection System

The configuration of the injection points is based on the geoforensic investigation explained by Zainuddin *et al.* (2021) shown in Figure 8. The construction of a grout curtain using the PU foam injection method at the edge of the piled embankment can plug the void and prevent migration of fill material into the cavities created due to the global settlement of the ground surrounding the bridge and culvert approaches. PU foam injection system was carried out during the midnight hours to avoid heavy traffic and complaint by the traffic user due to road closure. The photos of rehabilitation work using PU injection method are shown in Figure 9 and Figure 10. The quantity of PU foam needed to fill the cavities detected below the piled box culvert or piled embankment was calculated based on the analysis data from ERI and JKR Probes results provided by Zainuddin *et al.* (2021). About 2,605 liter of PU foam was injected below the bridge transition at Kuala Selangor bridge abutment and about 2,250 liter of PU foam was injected beneath the transition approach of culvert at Sg. Gulang-Gulang.

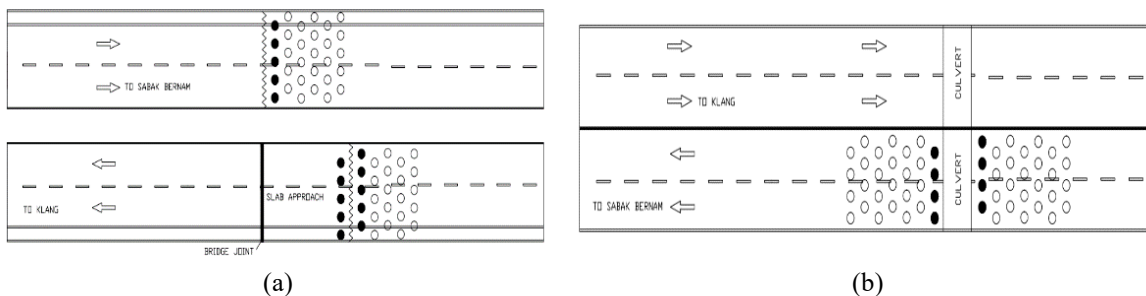


Figure 8. The area injected with PU foam at (a) Kuala Selangor Bridge (both direction of one of abutment); and (b) Culvert at Sg Gulang – Gulang (Route from Klang to Teluk Intan) (Zainuddin *et al.*, 2021).



Figure 9. Coring of the asphalt layer before injecting PU foam underneath the piled embankment (Zainuddin et. al., 2021).



Figure 10. Injecting the PU foam mixture at designated injection pressure in situ into the ground (Zainuddin et. al., 2021).

4. Settlement Monitoring

Deformation survey or deformation monitoring is the systematic measurement and tracking of the alteration in the shape or dimension of an object as a result of stresses induced by applied loads. Deformation survey is performed to detect and measure movements of the structure where it can detect relative or absolute movements toward the structure. Deformation survey is used to (Okiemute *et. al.*, 2018):

1. ascertain if movement have taken place;
2. to assess whether a structure is stable and safe;
3. analyzed the movement factors;
4. and its use to predict the future behavior of a structure.

Deformation survey requires accuracy to millimeters which depends on many factors which include from the techniques of deformation, type of measuring devices, the type of monitoring structures and requirements of adjustment use in detecting structure movements. Figure 11 and Figure 12 illustrate the close-up location of the settlement marker for settlement monitoring at Kuala Selangor Bridge and Sg. Gulang-Gulang Box Culvert, respectively. The monitoring of settlement was executed for 14 months to evaluate the performance of the PU foam injection as an alternative rehabilitation solution. The settlement markers were permanently fixed on the surface of the pavement and marked as SM 1 until SM 8 for each of location. At Kuala Selangor Bridge, the settlement markers located on the bridge are SM 1 and SM 6. Settlement markers SM 2, SM 3, SM 7 and SM 8 are located before/after transition of the bridge section, SM 4 and SM 5 are located on the ground at the median between two bridges. At Sg Gulang-Gulang Box Culvert, all the settlement markers were located outside the alignment of culvert/piled embankment.

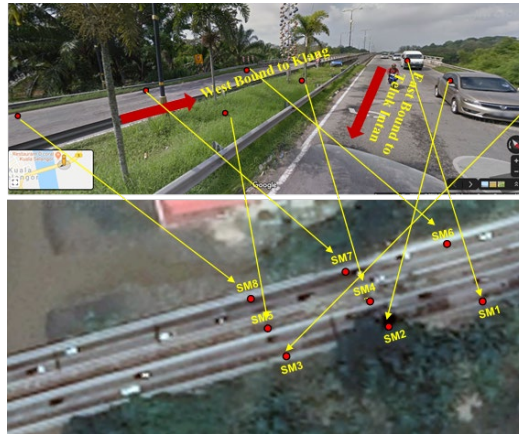


Figure 11. Location of the settlement markers at Kuala Selangor bridge approach.

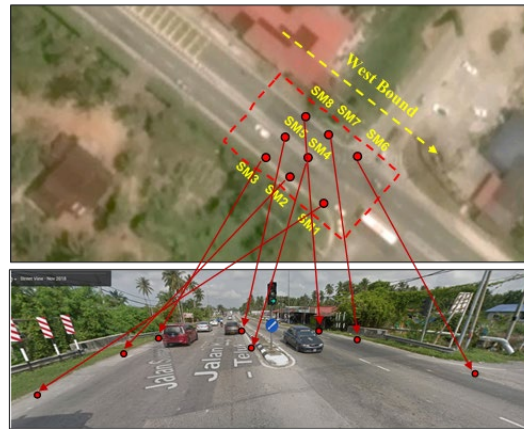


Figure 12. Location of the settlement markers at Sg. Gulang-gulang culvert approach.

3. Results and Analysis

The performance of the PU foam injection as an alternative ground rehabilitation method was monitored based on the deformation survey at every settlement marker. According to the geotechnical design requirement stipulated by the Public Works Department (PWD) (Jabatan Kerja Raya, 2019) for ground treatment and stabilisation, performance characteristics of the embankments are:

1. Differential settlement – Allowable settlement for five (5) years post construction:
 - i. within 50 m from structures < 100mm; and
 - ii. within 100 m remote from structures < 150mm for five (5) years post construction; and
2. Total settlement – Allowable settlement for road < 250mm for five (5) years post construction.

5.1 Section 481.7, Federal Route FT05 (Kuala Selangor Bridge)

Based on the eight (8) recorded data observed, it can be concluded that the settlement readings for all the settlement markers during the period of 14 months are considered within tolerable limits which is 250mm/5 year (total settlement) and 100 mm/5 years (differential settlement). After a year, at settlement markers SM 2 and SM 3 which is located on the compacted fill showed that the road experienced drastic settlement just after the PU foam injection location. PU foam expands and plug the edge of piled embankment and filled the cavities. At the same time, it densifies and increases the soil beneath the structures. The settlements at SM 4 and SM 5

are slowly increased because at median of the approach, there were no injection points located. All the data varied within 14 weeks due to uplifting since the buoyancy characteristic of the PU foam and rearrangement of soil particles to achieve a stable compaction condition. The deformation presented in Figure 13(a) and Figure 13(b) showed either settlement or uplifting due to buoyancy effect of the PU foam injected at Kuala Selangor Bridge.

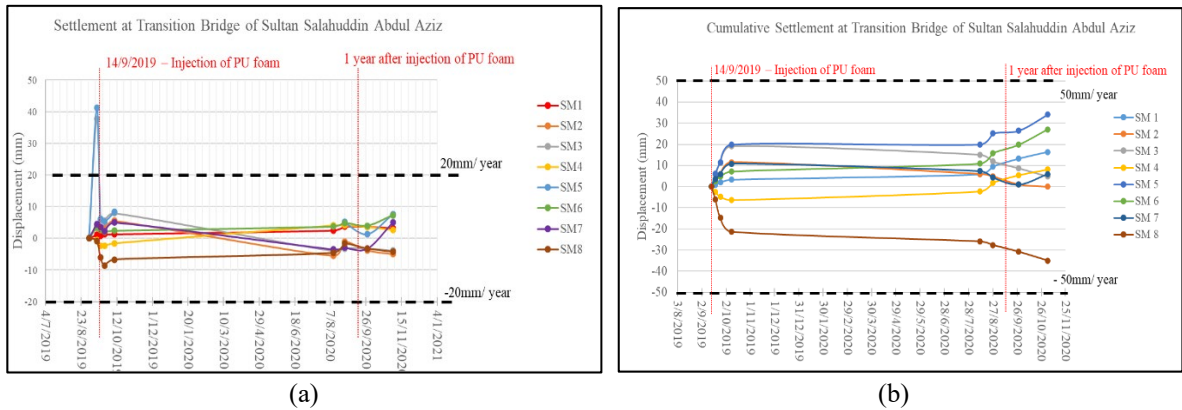


Figure 13. The deformation monitoring at the transition of Kuala Selangor Bridge (a) settlement (b) Cumulative settlement.

5.2 Section 491.8, Federal Route FT05 (Sg. Gulang-Gulang Box Culvert)

The deformation presented in Figure 14(a) and Figure 14(b) illustrated that the settlement is either increasing or decreasing after a year of improvement. From the observation of displacement monitored at Sg Gulang-gulang Box Culvert, displacements at settlement markers SM 6, SM 7 and SM 8 are more than the tolerable limit within a year for total settlement and near to the limit set for differential settlement. At settlement markers, SM 6, SM 7 and SM 8 located at west bound (slow lane direction from Teluk Intan to Klang), was not injected by PU foam due to limitation of cost for the georehabilitation solution and during that time, the route was already repaired by different method. Furthermore, the possibility of large settlements at SM 6, SM7 and SM 8 are due to the fact that the area is founded on loose compacted material, hence causing migration of the fill material into the enlargement of the void present underneath the piled box culvert. In addition, at settlement marker SM3, the settlement value is slightly excessive and there is presence of uplifting due to the lightweight capability of the PU foam.

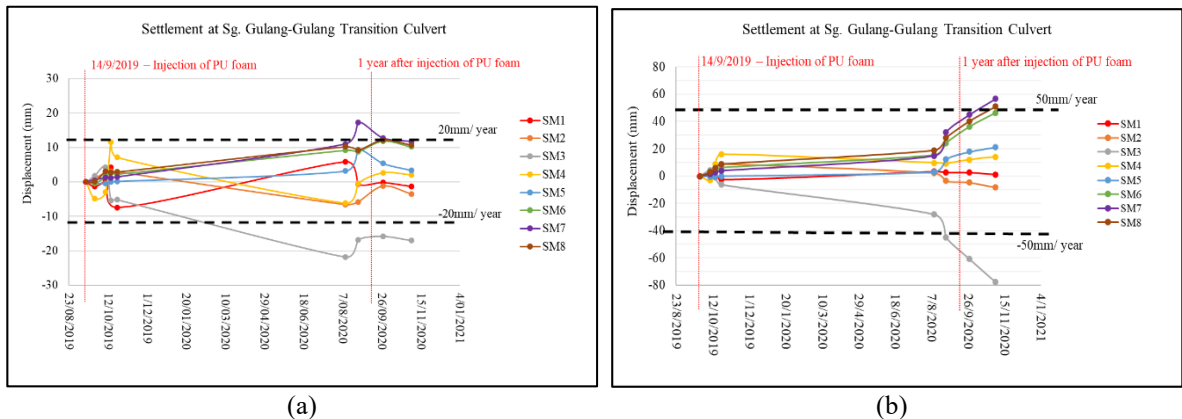


Figure 14. The deformation monitoring at transition box culvert (a) settlement (b) Cumulative settlement.

6. Conclusion and Recommendations.

Based on the settlement monitoring executed at the Kuala Selangor Bridge and Sg, Gulang-gulang Culvert approaches, the conclusions are given below:

1. The selection of the ground improvement method depends on the effectiveness of data analysis from field investigations. Based on these case studies, PU foam injection is found to be adaptable in mitigating the settlement at approach of box culvert within the study period.
2. Since PU foam is a lightweight material, therefore it needs adequate surcharge that can control its buoyancy effect. The limited data analysis could not conclude the performance of the PU foam injection method in the long term, However, PU foam injection method can be listed as one of the alternative georehabilitation solution to reduce the effect of differential settlement at bridge and culvert transition approaches.

Based on this study, it is recommended that the settlement monitoring be extended to evaluate the performance of the bridge and culvert transition approaches. In addition, this treatment is an alternative rapid solution without excavation, minimal road closure and stationed traffic diversion.

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Author Contributions

Ismacahyadi Bagus Mohamed Jais contributed to conceptualization, software, methodology, investigation, formal analysis and writing original draft

Abdul Samad Abdul Rahman contributed to writing review and editing, investigation, data curation and methodology

Fairul Zahri Mohamad Abas contributed to resources, project administration and funding acquisition.

Nurul Eilmy Zainuddin contributed to resources, project administration and funding acquisition.

Mohamed Azizi Md Ali contributed to conceptualization, investigation, resources, project administration and funding acquisition.

All authors read and approved the final manuscript.

Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

Declaration of Generative Ai in The Writing Process

No AI assistance used in this paper articles

Data Availability/Supplementary Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement

The research activities in not involved with human beings. No Ethics Statement required.

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