Performance Comparison between Polyurethane Injection Pile and Slab System against Lightweight Concrete as a Ground Improvement Using Finite Element Analysis

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Abstract
Excessive post construction and differential settlements constitute an engineering challenge for structures founded on soft cohesive soil which caused instability and crack to the existing structure. Inadequacy of design for foundation supporting structure during the early stage of construction and less information on site investigation might be the main reason for this problem. Various methods of remedial works have been proposed and implemented for the existing foundation which has been encountered with this settlement problem such as underpinning piles, grouting, pin piles and etc. However, most of these methods require major excavation and disturbance to the existing structure. To overcome this problem, polyurethane (PU) injection pile and slab is proposed to replace the conventional underpinning pile. No excavation is required and only a small diameter of hole is drilled on the existing slab foundation before injection of PU. Performance of this method is compared against lightweight concrete slab using finite element analysis called PLAXIS 2D.

Keywords: Settlement, Polyurethane, Finite Element Analysis, PLAXIS 2D

INTRODUCTION
Excessive post construction and differential settlements constitute an engineering challenge for structures founded on soft cohesive soil which caused instability and crack to the existing structure. Inadequacy of design for foundation supporting structure during the early stage of construction and less information on site investigation might be the main reason for this problem. Various methods of remedial works have been proposed and implemented for the existing foundation which has been encountered with this settlement problem such as underpinning piles, grouting, pin piles and etc. However, most of these methods require major excavation and disturbance to the existing structure. To overcome this problem, polyurethane (PU) injection pile and slab is proposed to replace the conventional underpinning pile. No excavation is required and only a small diameter of hole is drilled on the existing slab foundation before injection of PU. Performance of this method is compared against lightweight concrete slab using finite element analysis called PLAXIS 2D.

2. Problem statement:
Existing housing area at Section 7 Shah Alam, Selangor, Malaysia were experiencing excessive post construction settlement which caused serious crack to the houses as shown in Figure 1. The original foundation of the houses is pile to set with non-suspended slab system. About 600mm void was found in between the non-suspended slab and the underlying soil as shown in Figure 1. Further settlement is expected to occur if no soil treatment is carried out since the recent subsurface investigation carried out shows that soil underneath the non-suspended slab consist of very soft clay of about 15m deep.

During initial design, it is expected that the well compacted soil beneath the non-suspended slab should have had adequate bearing capacity to sustain
the load from the structure. However, from the site investigation carried out recently, the soil underneath the non-suspended slab is found to have very low strength and not well compacted leading to excessive post construction settlement. There are several methods of soil treatment and stabilization suggested to rehabilitate the house foundation such as underpinning piles, EPS, lightweight concrete (LWC), limeclay stabilization and etc. However, this method rather tedious to be carried out since major excavation is required underneath the houses. Therefore, Polyurethane (PU) Injection Pile and Slab System is proposed to control excessive settlement of soil and act as a void filler to the soil underneath the slab. Performance of PU is compared to lightweight concrete in order to evaluate the effectiveness of both methods.

3. Subsoil condition:

   Based on the subsurface investigation (S.I) carried out recently, the subsoil strata beneath the embankment generally consists of a layer of residual soil material (< 3m thick below ground level), previous backfilled to form embankment. Thereafter original clay layer (SPT-N ~ 0) of about 15m is encountered. Subsequently, stiff to hard clay layer is encountered at depth of 15m below existing ground level would be incorporated in the model for the analyses at later stage. Figure 2 present the borehole profile and the major/minor components of soil classification together with SPT-N value.

Fig. 1: Defect area of the existing house.

Fig. 2: Subsoil Profile based on Borelog.

Fig 3: Plasticity Chart.

Fig. 4: T-S Plot to determine shear strength parameter of soil.
3.1 Physical Properties:

The subsoil descriptions in the profile are classified using the results of laboratory classification tests and in accordance to “British Soil Classification System (BSCS)”, BS 5950: 1999.

From the soil classification tests and Atterberg Limit tests carried out, the subsoil mainly consists of SILT and CLAY material. From the plasticity chart as shown in Figure 3, the liquid limit (LL) of the collected samples during subsurface investigation ranges from about 30% to 120% whereas, the plastic index (PI) varies from 7% to 64%. Most of the data points scattered above the “A” line and this implies that the overburden materials (selected for testing) generally consist of intermediate to high plasticity CLAY in the fine component of the soil composition.

3.2 Shear Strength Parameters:

Isotropically Consolidated Undrained (CIU) Triaxial test with pore water pressure measurements have been carried out to determine the effective shear strength parameters. CIU tests were carried out on three (3) recovered undisturbed (UD) samples and the results were presented in t-s plot as shown in Figure 4. As shown in the figure, the effective cohesion, c’ of 5kPa, and the effective friction angle, $\phi^\prime$ of 10$^\circ$ are interpreted for the overburden soil.

3.3 Groundwater Profile:

Based on the field records, it is observed that the ground water level (GWL) at the embankment area is high with highest recorded value is 0.6m below the existing ground level. The GWL profile would then be adopted in the analyses at later stage.

4. Remedial Works:
4.1 Pu Injection Pile/Slab System:

Polyurethanes (PU) are an extensive family of polymers that can be manufactured to achieve a wide range of physical characteristics in either expanded or non-expanded states. Expanding PU are formed from an exothermic reaction between a polyol and an isocyanate, mixed in specific volumetric proportions. A large amount of carbon dioxide is produced during the reaction causing volume expansion and producing a foam structure where gas bubbles (cells) are surrounded by rigid wall. The pressure exerted during expansion and the subsequent density of the PU depends on the extent to which the gas in the bubbles are able to expand before PU hardened [2].

Injection of polyurethane (PU) pile and slab is an alternative method to pile underpinning works to solve the problem of excessive total settlement and differential settlement of building houses. The pressure exerted by evolved gas during chemical reaction forms the resin to lift up the structure. PU can easily be installed by drilling small diameter of hole followed by injection of PU using about 30mm diameter geotextile shell tubes. The depth of the PU injection pile is about 5m. No excavation is required. The injected PU is expected to expand about fifteen to thirty times of diameter tube.

An installed PU pile is a geotextile shell filled with an expanded resin that can have a compressive strength of 1MPa to 16MPa. Using geotechnical borehole information, resin quantities are predetermined and computer-monitored. As the compressed element is expanded from the bottom up, adjacent weak ground is displaced and compacted as shown in Plate 1. The resin hardens and there is immediate increased support. The shape of the PU Pile should be irregular, the shape being affected by the varying strength of ground resistance at the different depths.

4.2 Lightweight Concrete (Lwc) Slab:

Construction of concrete slab is an alternative to PU pile and slab to remedy the void and crack of the existing slab. This is a conventional method and required major excavation and disturbance to the existing structures. In this study, lightweight concrete slab is used instead of normal concrete slab in order to reduce the self-weight of slab foundation imposed to underlying soil thus reduce the post construction settlement. Lightweight concrete slab is proposed to improve bearing capacity of soil underneath the non-suspended slab. Major excavation is required under the existing non-suspended slab in order to construct lightweight concrete slab between existing slab and underlying soil. The existing slab need to be demolished in order to construct the lightweight concrete slab to replace the existing slab which has been damaged caused by the excessive post construction settlement.

Performance Of Polyurethane (Pu) Against Lightweight Concrete (Lwc) From Plaxis Analysis:

Subsoil between the pile (underneath the non-suspended slab) had settled significantly before remedial works and post-construction settlement of the subsoil from analysis after 5 years construction period is about 300mm which is more than the allowable post-construction settlement (after 5 years post-construction) of 250mm by JKR guideline for embankment on soft ground and 75mm by Skempton& MacDonald, 1956 for two-storey houses. This is due to the large pile-to-pile spacing of about 2.0m to 5.0m and soil underneath the non-suspended slab consists of very soft clay to about 15m in depth. On top of that the measured angular distortion is about 1/10 which has exceeded the allowable value of 1/350 [8]. From the results of the analysis, it shows that excessive settlement had been occurred at the abovementioned area. This result tally to actual site condition which serious
crack was found all over the houses and large void was traced underneath the slab. The maximum settlement of subsoil was occurred at the centre of pile to pile.

**Plate 1:** View of PU Injection Pile below Ground (after Philip M, 2010, URETEK Ground Engineering).

After injection of polyurethane as remedial measures, the settlement of the subsoil is only about 5mm which complied to the maximum allowable long term post-construction settlement which is lesser than 75mm. Average total uniform load from the two-storey building taken as 25kPa acting on the slab. The maximum angular distortion ($\frac{\Delta \rho}{L}$) is about 1/500 which is better than 1/350 [8], for two-storey building in order to prevent cracking on building. Injection of PU helps to eliminate excessive settlement by filling the void between the soils particles with insignificant weight imposed to the underlying soil. On the other hand, the settlement after construction of lightweight (LWC) concrete slab is about 1.4mm with angular distortion of 1/1250. This method also helps to reduce settlement by providing rigid foundation with minimal weight imposed to the underlying soil. This value shows that both settlement criteria are complied. The results from PLAXIS analysis is compared between PU and LWC as shown in Figure 5. The settlement profiles for both methods are summarized and plotted as shown in Figure 6.

Results from analysis shows that both methods can help to eliminate the excessive settlement of the subsoil underneath the houses. PU injection uses a simple construction method, fast to construct and cause minimal disturbance to existing structure. On the other hand, LWC slab required major excavation and removal of existing slab which has been damaged by the excessive settlement in order to construct new LWC slab. The settlement criteria is complied for both methods however, PU injection is the most efficient remedial works to eliminate excessive settlement with very minimal disturbance to existing structure and surrounding compared to lightweight concrete. As the embankment and the foundation for the house has been existed for long, therefore all the subsoil layer has been modeled in drained condition. This has resulted in minimal excess pore pressure from the subsoil for both construction methods as shown in Figure 7.

6. **Cost comparison between pu and lwc:**

As shown in Table 2.1, cost of PU injection is around RM23/L [10], which is equivalent to RM23000/cum inclusive equipment and labor whereas for lightweight concrete (LWC) as shown in Table 2.2, the rate is around RM500/cum [10]. However, PU injection quantity would not need as much as LWC since PU can expand up to 30 times. From the calculation that has been made based on the rate given, the cost of PU twice the cost of LWC.

**Fig. 5:** Results of analysis for PU vs LWC construction works.
**Fig. 6:** Settlement profile for construction works of PU vs LWC.

**Fig. 7:** Excess Pore Pressure for construction works of PU vs LWC.

**Table 2.1:** Sample Quotation showing rate of PU [10].

<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION OF WORKS</th>
<th>UNIT</th>
<th>RATE (RM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Mobilization And Demobilization</td>
<td>L/S</td>
<td>5,000.00</td>
</tr>
<tr>
<td>2.0</td>
<td>To Supply And Pumping Low Pressure Void Filling Polyurethane Injection System</td>
<td>Lit</td>
<td>23.00</td>
</tr>
<tr>
<td></td>
<td>*Price quoted inclusive of equipments and labour</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.2:** Sample Quotation showing rate of LWC and Associated Work [10].

<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION OF WORKS</th>
<th>UNIT</th>
<th>RATE (RM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Dayworks - Plant</td>
<td>per 8hr/day</td>
<td>460.00</td>
</tr>
<tr>
<td></td>
<td>Allow for mobile air compressor, water tanker, etc.</td>
<td>day</td>
<td>200.00</td>
</tr>
<tr>
<td>2.0</td>
<td>Lightweight Concrete and other Ancillary Works</td>
<td>cu.m</td>
<td>500.00</td>
</tr>
<tr>
<td></td>
<td>Supply and lay lightweight concrete with dry density of 1000 kg/m3 and Compressive Strength of 2MPa. The application is based on specialist specific requirement for the stabilisation works.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Formwork</td>
<td>sq.m</td>
<td>35.00</td>
</tr>
<tr>
<td>4.0</td>
<td>Earthwork and Turfing</td>
<td>Excavation of earth including the loose earth manually earth benching as directed by the Engineer on site</td>
<td>cu.m</td>
</tr>
</tbody>
</table>

No literature found on finite element analysis of PU injection pile to remediate excessive post construction and differential settlement problem of existing structure. The comparison between performance of PU injection pile/slab against lightweight concrete slab for remedial work of existing structure also have not been found in the literature.

**Conclusion and recommendation:**

The analysis is carried out in a small scale and back analysis of the existing condition is proved to have caused excessive settlement which caused serious crack to the houses and occurrence of large void underneath the slab. Large total settlement and angular distortion which is about 300mm and 1/10 respectively are obtained in the analysis. This value indeed has exceeded the allowable settlement criteria by JKR.

For analysis on the remedial works using either PU or LWC slab, it depends as well on the properties of the material been used and the type of analysis been performed. The properties used are based on the available market material. From the analysis, it shows that excessive settlement been reduced and eliminated to be lesser than the allowable settlement and angular distortion. This will guarantee the houses in a good condition with no further cracks or
any other defects related to the excessive settlement problem.

The analysis is performed to predict future condition of the subsoil, nonetheless site construction works is a real works that will be carried out at site. Therefore, the material properties used in the model should represent the actual site condition so that the results from analysis would be very useful to predict the site conditions.

Injection of PU helps to eliminate excessive settlement by filling the void between the soils particles with insignificant weight imposed to the underlying soil. On the other hand LWC slab also helps to reduce settlement by providing rigid foundation with minimal weight imposed to the underlying soil. Settlement criteria using both methods are complied. Performance of PU and lightweight concrete are almost equivalent as shown by settlement profile and excess pore pressure from PLAXIS analysis. However, PU is better than LWC in term of construction, easy and fast installation without much disturbance to existing structure as the installation only using small diameter of tube about 30mm. In term of cost, PU cost is higher than LWC which is about twice the rate of LWC.

On site PU performance to stabilize the soil and increase shear strength and bearing capacity of soil has been proven by many case studies of PU construction in Malaysia and abroad.

Since PU is a new ground improvement method, some recommendations are discussed as follows in order to further improve the performance of PU:

1) Results of PLAXIS analysis should be further verified by monitoring settlement at site during and after construction of remedial works using settlement marker.
2) More technical paper on real PU performance and cost comparison have to be produced to increase confident level of engineer/developer to use this method in their related construction works
3) Since PU is a new in ground improvement and hardly to find literature review on the long term performance of PU on site, therefore performance of the finished construction using PU in long term have to be monitored very closely so that it will become a reference for other

References