Prediction of Deflection of Single-pile Nailed-slab by Using the Allowable Equivalent Modulus of Subgrade Reaction in Case of Additional Modulus from Modified Hardiyatmo Method

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Abstract. An equivalent modulus of subgrade reaction was proposed for analyzing the Nailed-slab Pavement System. This modulus is defined by accumulating the modulus of subgrade of the slab and the additional modulus of subgrade reaction which is contributed by a pile under the slab. The additional modulus can be defined by the Modified Hardiyatmo Method. The equivalent modulus of subgrade reaction only considers a safety factor for additional modulus of subgrade reaction. In this research, a global safety factor will be considered for all modulus. This research is aimed to learn the prediction of the slab deflection by using the allowable equivalent modulus of subgrade reaction. The global safety factor was varied by 1.0, 2.0; 2.5; and 3.0. The slab deflection was calculated by using Beam on Elastic Foundation. Data of the nailed-slab and the soil were based on the previous researcher for a single pile nailed-slab model. Results show that the calculated deflection of the slab was in good agreement with the observed deflection. Increasing the global safety factor resulted in the over-estimated slab deflections. It means the design by using allowable equivalent modulus of subgrade reaction tends to result in a safety zone.

1. Introduction

Physical modeling of nailed-slab and its analytical study have been conducted for soft clay ([1],[2], [3], [4], [5], [6], [7], [8], [9], [10]). An equivalent modulus of subgrade reaction was proposed to analyze the Nailed-slab System ([3], [4], [6], [7], [8], [9], [11], [12], [13], [14]). The equivalent modulus of subgrade reaction is cumulative of the modulus of subgrade reaction of the slab ($k$) and additional modulus of subgrade reaction ($\Delta k$). The additional modulus of subgrade reaction based on the relative displacement between the pile and soils was used [4]. The development of the formula was based on static theory. A new approach for practical purposes in designing the Nailed-slab System was proposed [7]. This approach considered that the pile friction resistance is fully mobilized and a tolerable settlement is adopted. The proposed method of analysis is applied on one row of the pile of the Nailed-slab. In the practice, the Nailed-slab will be constructed by multiple rows of piles. This system will have higher capacity and stiffness. Hence, designing the Nailed-slab System based on an analysis of the one-row pile will produce a safe design ([7], [9]).

In designing the Nailed-slab, it is required an equivalent modulus of subgrade reaction due to pile bearing contribution ($k'$). The analytical approach of this modulus is determined by accumulating the
modulus of subgrade reaction of the slab \((k)\) and the additional modulus of subgrade reaction \((\Delta k)\). The \(\Delta k\) is representing the contribution of the installed pile under the slab. The equivalent modulus of subgrade reaction \((k')\) is given as follows ([4], [3], [6], [7]):

\[
k' = k + \Delta k
\]

where \(k\) is the modulus of subgrade reaction from plate load test \((\text{kN/m}^3)\), \(\Delta k\) is the additional modulus of subgrade reaction \((\text{kN/m}^3)\).

The mobilization of unit friction resistance of pile shaft is ranged in the elastic zone [7]. Safety factor 2.5 is usually used in the practice of determining the pile allowable bearing capacity. Then the additional modulus of subgrade reaction \((\Delta k)\) can be defined by the Modified Hardiyatmo Method (Equation (2)). In this case, the end bearing resistance of the pile is neglected due to the small dimension of the pile and the embedded pile in soft soils.

\[
\Delta k = \frac{f_s A_s}{2.5 \delta_a A_{ps}}
\]

where \(\delta_a\) is the tolerable settlement of rigid pavement slab \((\text{m})\), \(f_s\) is the ultimate unit friction resistance of pile shaft \((\text{kN/m}^2)\), \(A_s\) is the surface area of pile shaft \((\text{m}^2)\), \(A_{ps}\) is the area of plate zone which supported by a single pile \((\text{m}^2)\), and 2.5 is the safety factor. And the equation (2) can be written as [9]

\[
\Delta k = \frac{f_s A_s}{SF \delta_a A_{ps}}
\]

The end bearing resistance of pile can be ignored for nailed-slab which resting on soft soils. Previous researchers were applied Equation (3) with variation in \(SF\) ([15], [16]).

According to equation (1), (2), and (3), the safety factor is only considered for additional modulus. In this research, a safety factor will be considered for all modulus of Equation (1). Hence, equation (1) is written as

\[
k'_a = \frac{k'}{SF_G}
\]

\[
k'_u = \frac{k' + \Delta k_m}{SF_G}
\]

where \(k'_a\) is the allowable equivalent modulus of subgrade reaction \((\text{kN/m}^3)\), and \(SF_G\) is a global safety factor. Since Equation (4) has a global safety factor, a safety factor in Equation (2) and (3) should be neutral \(1.0\). Then the additional modulus of subgrade reaction should be deformed as a modified additional modulus of subgrade reaction \((\Delta k_m)\).

\[
\Delta k_m = \frac{f_s A_s}{\delta_a A_{ps}}
\]

This paper is aimed to learn the prediction of the slab deflection by using the allowable equivalent modulus of subgrade reaction. In this case, a single-pile nailed-slab that loaded on concentric load will be considered.

2. Methodology

Puri [13] presented the detail of the procedure on single-pile full-scale Nailed-slab and briefly described also in Puri, et.al. ([11], [17]). The single-pile full-scale nailed-slab was constructed on soft clay. The model was loaded by a hydraulic jack on the center of the slab. The loads were transferred to the slab surface by using a circular steel plate. Slab deflections were measured by dial gauge on the center of the slab and each corner of the slab. Figure 1 shows the schematic diagram of the testing investigation and Figure 2 presents photographs of the investigation [13].
Figure 1. Schematic Diagram of The Testing Investigation: a). Plan View; b). Cross Section and Loading Equipment [13].

Figure 2. Photographs of Concentric Loading Test on The Single-Pile Nailed-Slab System [13].

The soft clay properties are presented in Table 1. The slab and piles were reinforced concrete. The concrete strength characteristic of the slab and piles was 29.2 MPa and 17.4 MPa respectively. The flexural strength of the slab was 4,397.6 kPa. The coefficient of subgrade reaction was 15,000 kPa/m based on the standard plate load test. The corrected coefficient was 3,750 kPa/m based on the dimension and shape of the slab [18].
### Table 1. Soft Clay Properties [11]

| Parameter                     | Unit | Average |
|-------------------------------|------|---------|
| Specific gravity, $G_s$       |      | 2.55    |
| Consistency limits:           |      |         |
| - Liquid limit, $LL$          | %    | 88.46   |
| - Plastic limit, $PL$         | %    | 28.48   |
| - Shrinkage limit, $SL$       | %    | 9.34    |
| - Plasticity index, $PI$      | %    | 59.98   |
| - Liquidity index, $LI$       | %    | 0.36    |
| Water content, $w$            | %    | 54.87   |
| Clay content                  | %    | 92.93   |
| Sand content                  | %    | 6.89    |
| Bulk density, $\gamma$        | kN/m$^3$ | 16.32  |
| Dry density, $\gamma_d$       | kN/m$^3$ | 10.90  |
| Undrained shear strength, $s_u$ | kN/m$^2$ | 20.14  |
| CBR                            | %    | 0.83    |
| Soil classification:          |      |         |
| - AASHTO                      | -    | A-7-6   |
| - USCS                         | -    | CH      |

Figure 3 shows the $P$-$\delta$ relationship for loading tests. The installed pile under the slab reduced slab settlement and increased the bearing capacity of the structure. The elastic condition reached about 30 kN.

![Figure 3. $P$-$\delta$ Relationship for Loading Tests of Single-Pile Nailed Slab [13].](image)

The $SF_G$ was varied by 1.0; 2.0; 2.5 and 3.0. An analysis of the deflection was calculated by the theory of Beams on the Elastic Foundation (BoEF). The BoEF analysis was conducted by using the “BoEF.xls software version 1.4”. According to the limitation of BoEF, some simplification has to be done ([9], [13]), neglecting the lean concrete reaction modulus and slab thickening. Since the slab thickening was neglected, then the pile length was adjusted by adding the thickness of slab thickening with the initial pile length. The comprehensive analysis procedure is presented in Puri, et.al [11], and Puri [9]. Briefly, the analysis procedure as follows: a) calculating the corrected coefficient of subgrade reaction of the soft clay under the slab (corrected due to the dimension and the shape of the slab—in this study, the correction based on Das method [16]), b) calculating the modified additional modulus
of subgrade reaction of the soft clay by using Equation (5) (the tolerable settlements ($\delta_a$) were taken by using observed deflections), c) calculating the equivalent modulus of subgrade reaction, d) calculating the allowable equivalent modulus of subgrade reaction by using Equation (4b), e) calculating the inertia moment of the slab, f) input the required parameters into BoEF software, and g) investigate the results (output of the bearing pressure is not considered).

3. Results and Discussion

3.1. Allowable Equivalent Modulus of Subgrade Reaction

The soil modulus of subgrade reaction for 1.20 m slab width was 4,500 kPa/m. The equation (5) was used to calculate the modified additional modulus of subgrade reaction due to single-pile installation under the slab; the results are shown in Table 2 by variation in safety factor. The tolerable settlements ($\delta_a$) were taken by using maximum observed deflections. Allowable equivalent modulus of subgrade reaction is included in Table 2.

| Load, $P$ (kN) | $\delta_s = \delta_s$ (mm) | $SF_G$ | $\Delta k_m$ (kN/m$^3$) | $k_{a'}$ (kN/m$^3$) |
|----------------|------------------|--------|----------------|----------------|
| 5              | 0.24             | 1.0    | 66200.71       | 1.0            |
|                |                  | 2.0    | 33100.36       | 2.0            |
|                |                  | 2.5    | 26480.28       | 2.5            |
|                |                  | 3.0    | 22066.90       | 3.0            |
| 10             | 0.48             | 1.0    | 35803.09       | 1.0            |
|                |                  | 2.0    | 17901.54       | 2.0            |
|                |                  | 2.5    | 14321.23       | 2.5            |
|                |                  | 3.0    | 11934.36       | 3.0            |
| 20             | 0.98             | 1.0    | 19689.80       | 1.0            |
|                |                  | 2.0    | 9844.90        | 2.0            |
|                |                  | 2.5    | 7875.92        | 2.5            |
|                |                  | 3.0    | 6563.27        | 3.0            |
| 40             | 2.95             | 1.0    | 4783.35        | 1.0            |
|                |                  | 2.0    | 4783.35        | 2.0            |
|                |                  | 2.5    | 3826.68        | 2.5            |
|                |                  | 3.0    | 3188.90        | 3.0            |
| 60             | 5.86             | 1.0    | 7048.05        | 1.0            |
|                |                  | 2.0    | 7048.05        | 2.0            |
|                |                  | 2.5    | 2819.22        | 2.5            |
|                |                  | 3.0    | 2349.35        | 3.0            |

3.2. Result of Slab Deflection

The results of the deflection analysis are shown in Figure 4. Good results are obtained in the sense that the calculated settlement is in very good agreement with observation for $SF_G = 1.0$. For $SF_G = 1.0$, the over-estimated about 34% for maximum load 60 kN. The modified additional modulus of subgrade reaction ($\Delta k_m$) was done by using the tolerable settlements ($\delta_s$) which were taken from observed deflections. In case this proposed method to be used for preliminary design analysis, the design could
have an additional safety level. Because the \( \delta_a \) should not exceed 5 mm to avoid the surface crack of the concrete slab.

\( SF_G \) variation affects the calculated deflections. All calculated deflection based on the variation of \( SF_G \) tends to over-estimate. The over-estimated tends to increase by increasing in \( SF_G \). For \( SF_G = 3.0 \), the over-estimated about 229% for maximum load.

![Figure 4. P-\( \delta \) relationship on loading point of single-pile nailed-slab by variation of \( SF_G \).](image)

It is also shown in Figure 4 that \( P-\delta \) curves are in the elastic-plastic zone which is deferred with the theory. Higher the \( SF_G \), elastic-plastic behavior is weaker. In this case, the Poisson’s ratio did not influence the slab deflections [13]. The BoEF analysis is two dimensional (2D). Poisson’s ratio can influence the inner stresses. Hence, the failure criteria of the slab will increase. This means that the preliminary design by using Equation (4) will be in the safety zone.

4. Conclusions
This paper introduced the allowable equivalent modulus of subgrade reaction and the modified additional modulus of subgrade reaction. The additional modulus of subgrade reaction was calculated by Modified Hardiyatmo Method. The deflection of the slab was calculated by variation in the global safety factor and compared to the observed deflection. Results show that the calculated deflection of the slab was in good agreement with the observed deflection. Increasing the global safety factor resulted in the over-estimated slab deflections. In case this proposed method to be used for preliminary design analysis, the design could have an additional safety level. Because the \( \delta_a \) should not exceed 5 mm to avoid the surface crack of the concrete slab. Others, in the field, this Nailed-slab pavement system would be constructed by many numbers of pile rows that could increase the stiffness of the system. Hence, the slab deflections would be smaller. It means the design by using allowable equivalent modulus of subgrade reaction tends to result in a safety zone. Then, this research should be followed up by further research which is considering the number of pile rows.

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