

# Prediction the Maximum Deflection of the Prototype of Nailed-slab Pavement System Using the Allowable Equivalent Modulus of Subgrade Reaction

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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.

**Keywords:** rigid pavement, safety factor, soft clay, modulus of subgrade reaction.

## 1. Introduction

Rigid pavement types on soft subgrade can cause damage to the pavement. Efforts to overcome these problems include improving the subgrade soil using geosynthetics (Harinder & Shankar, 2018), the use of rigid pavement of the Chicken Claw System (Hardiyatmo & Suhendro, 2003), and the use of rigid pavement of the Nailed-slab System (Hardiyatmo, 2008; Puri, et.al. 2011a; Puri, et.al. 2015). Concrete materials for rigid pavement can also be developed by adding waste additives such as corn stalk ash (Dewi, et.al., 2019; Mildawati, et.al., 2022).

Some previous researchers have been conducted some physical modeling of Nailed-slab pavement system and it's analytical studies for soft clay (Hardiyatmo & Suhendro, 2003; Hardiyatmo, 2008; Hardiyatmo, 2009; Hardiyatmo, 2011; Puri, et.al. 2011a; Puri, et.al. 2011b; Puri, et.al. 2012a; Puri, et.al. 2012b; Puri, 2015; Puri, et.al. 2017). An equivalent modulus of subgrade reaction was proposed in analysis the Nailed-slab System (Hardiyatmo, 2009; Hardiyatmo, 2011; Puri, et.al. 2011b; Puri, et.al. 2012a; Puri, et.al. 2012b; Puri, et.al. 2013a; Somantri, 2013; Puri, et.al. 2013b; Puri, 2015; Oktavia, et.al. 2018; Puri, et.al. 2019).

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 (Hardiyatmo,

2011). The development of the formula was based on static theory.

A new approach for practical purposes in designing the Nailed-slab System was proposed (Puri, et.al. 2012a). 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 (Puri, et.al. 2012a; Puri, 2015).

Puri, et.al. (2021) proposed the allowable equivalent modulus of subgrade reaction  $k'_a$  by considering a global safety factor  $SF_G$  and could be defined as

$$k'_a = \frac{k}{SF_G} \quad (1a)$$

$$k'_a = \frac{k + \Delta k_m}{SF_G} \quad (1b)$$

where  $k'_a$  is the allowable equivalent modulus of subgrade reaction ( $\text{kN/m}^3$ ), and  $SF_G$  is a global safety factor,  $k$  is the modulus of subgrade reaction from plate load test ( $\text{kN/m}^3$ ), and  $\Delta k_m$  is the modified additional modulus of subgrade reaction. The  $\Delta k_m$  should be determined by Eq.(2).

$$\Delta k_m = \frac{f_s A_s}{\delta_a A_{ps}} \quad (2)$$



the testing investigation and Figure 2 presents photographs of the investigation (Puri, et.al. 2014).

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 (according to Das, 2011).



Fig. 2 Photographs of loading test on the edge of slab in the 3-pile row nailed-slab system (Puri, et.al. 2013b).

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.

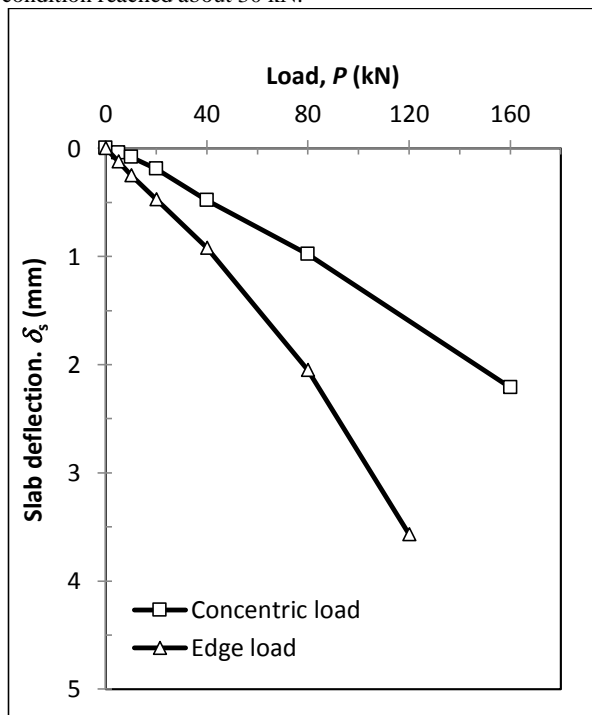


Fig. 3.  $P-\delta$  relationship for loading tests of 3-pile row nailed slab under repetitive loadings for the 5<sup>th</sup> repetition (Puri, et.al. 2014).

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 (Puri,

2015; Puri, et.al 2014), 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 described in Puri, et. all (2013a), and Puri (2015). Even though the Nailed-slab Pavement System consists of many pile rows, only one pile row to be considered in analysis. Briefly, the analysis procedure as follows:

- 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 (Das, 2011),
- calculating the modified additional modulus of subgrade reaction by using Equation (2) (the tolerable settlements ( $\delta_a$ ) were taken by using observed deflections),
- calculating the allowable equivalent modulus of subgrade reaction by using Equation (1),
- calculating the inertia moment of the slab,
- input the required parameters into BoEF software,
- investigate the results (output of the bearing pressure is not considered).

Table 1. Soft clay properties (Puri, et.al. 2013a, Puri, et.al. 2013b; Puri, et.al. 2014)

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 <sup>3</sup>	16.32
Dry density, $\gamma_d$	kN/m <sup>3</sup>	10.90
Undrained shear strength, $s_u$	kN/m <sup>2</sup>	20.14
CBR	%	0.83
Soil classification:		
- AASHTO	-	A-7-6
- USCS	-	CH

### 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. It seems that the  $\Delta k_m$  and  $k_a'$  tend to decrease by increasing the loads because of the increase in slab deflection. The  $\Delta k_m$  and  $k_a'$  tend to decrease also by increasing the global safety factor,  $SF_G$ . Similar results were also found in the additional modulus of subgrade reaction and equivalent modulus of subgrade reaction which decrease by increasing the loads (Puri, 2017b; Puri, et.al. 2016). Increasing of  $SF$  in the additional modulus of subgrade reaction decreases the equivalent modulus of subgrade reaction (Puri, 2017b; Puri, et.al. 2016).

Table 2. Allowable equivalent modulus of subgrade reaction  $k_a'$  for concentric load by various  $SF_G$

No.	Load, $P$ (kN)	$\delta_a$ (mm)	$\Delta k_m$ (kN/m <sup>3</sup> )	$k'$ (kN/m <sup>3</sup> )	$k_a'$ (kN/m <sup>3</sup> )			
					1.00	2.00	2.50	3.00
1	5	0.04	32,016.34	35,901.31	35,901.31	17,950.66	14,360.52	11,967.10
2	10	0.08	16,008.17	19,893.14	19,893.14	9,946.57	7,957.26	6,631.05
3	20	0.19	6,740.28	10,625.25	10,625.25	5,312.63	4,250.10	3,541.75
4	40	0.48	2,668.03	6,553.00	6,553.00	3,276.50	2,621.20	2,184.33
5	80	0.98	1,306.79	5,191.76	5,191.76	2,595.88	2,076.70	1,730.59
6	160	2.21	579.48	4,464.45	4,464.45	2,232.23	1,785.78	1,488.15

Table 3. Allowable equivalent modulus of subgrade reaction  $k_a'$  for edge load by various  $SF_G$

No.	Load, $P$ (kN)	$\delta_a$ (mm)	$\Delta k_m$ (kN/m <sup>3</sup> )	$k'$ (kN/m <sup>3</sup> )	$k_a'$ (kN/m <sup>3</sup> )			
					1.00	2.00	2.50	3.00
1	5	0.12	10,672.11	14,557.08	14,557.08	7,278.54	5,822.83	4,852.36
2	10	0.25	5,122.61	9,007.58	9,007.58	4,503.79	3,603.03	3,002.53
3	20	0.47	2,724.80	6,609.77	6,609.77	3,304.89	2,643.91	2,203.26
4	40	0.92	1,392.01	5,276.98	5,276.98	2,638.49	2,110.79	1,758.99
5	80	2.05	624.71	4,509.68	4,509.68	2,254.84	1,803.87	1,503.23
6	120	3.57	358.73	4,243.70	4,243.70	2,121.85	1,697.48	1,414.57

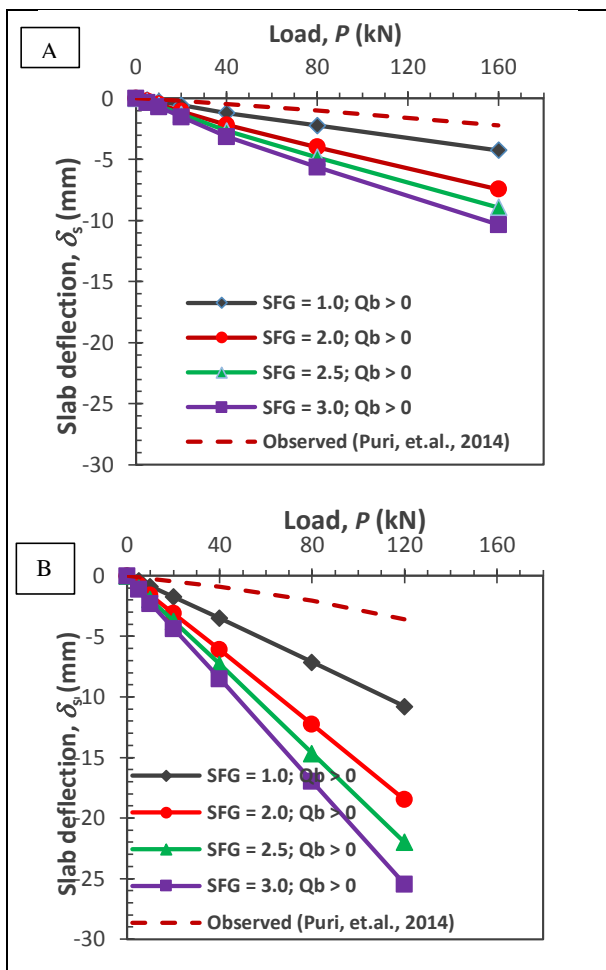


Fig. 4.  $P$ - $\delta$  relationship on loading point by variation of  $SF_G$ : a) concentric loads, b) edge loads.

### 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 ( $\delta_a$ ) 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.

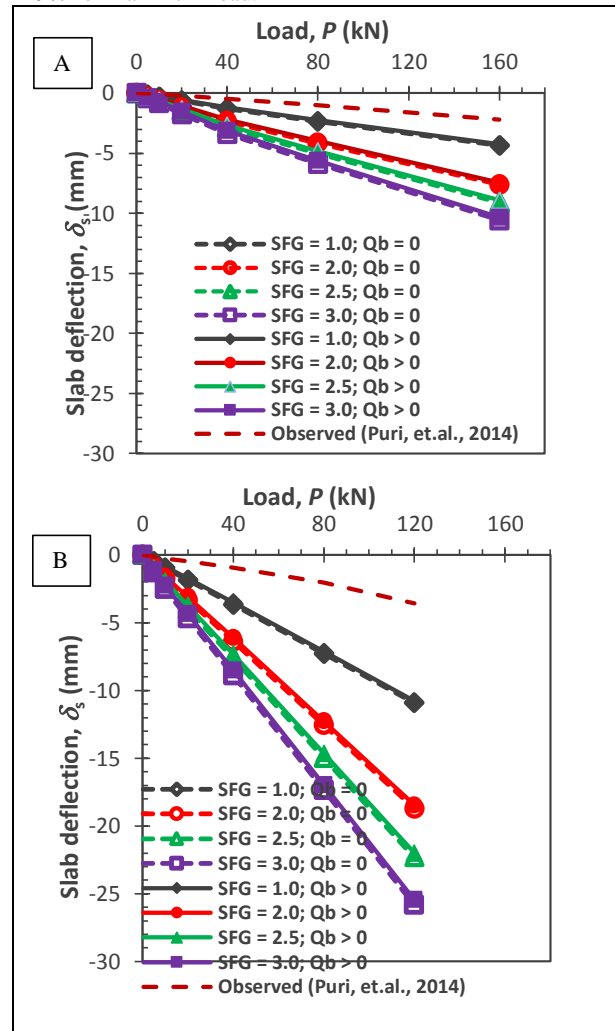


Fig.5. Effects of end bearing resistance  $Q_b$  on  $P$ - $\delta$  relationship by variation of  $SF_G$ : a) concentric loads, b) edge loads.

It is also shown in Figure 5 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 (Puri, 2107). 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.

End bearing resistance of pile  $Q_b$  was not significantly affect the slab deflection as shown in Figure 5. It was caused that the pile tip in soft clay and the pile dimension was smaller.

#### 4. Conclusion

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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