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DEVELOPING CURVE OF DISPLACEMENT FACTOR FOR DETERMINATION OF ADDITIONAL MODULUS OF SUBGRADE REACTION ON NAILED-SLAB PAVEMENT SYSTEM

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ABSTRACT

The pavement of the nailed-slab system has been proposed as an alternative solution for addressing the rigid pavement problem in soft soils. This system is used for developing a rigid pavement. The simple method of using an equivalent modulus of subgrade reaction (k') in nailed-slab system analysis was proposed by a previous researcher. This modulus consists of the modulus of subgrade reaction from a plate load test (k) and an additional modulus of subgrade reaction due to pile installing (Δk). The additional modulus of subgrade reaction has been proposed by some authors. The displacement factor was used in determining the additional modulus of subgrade reaction. This factor is difficult to define. In this research, the prototype test of a nailed slab with single-pile installation was conducted to learn the validation of the theory of the additional modulus of subgrade reaction on a full-scale dimension. The prototype was constructed on soft clay, and the connection between the pile and slab was perfect monolithically. This system was loaded by centric load. A new curve of the displacement factor is proposed. Calculated deflections based on this curve were compared to the observed deflection and resulted in good agreement with the observation. Hence, it can be used in preliminary design.

Keywords: Displacement factor; Nailed-slab system; Rigid pavement; Soft clay; Subgrade modulus

1. INTRODUCTION

The new proposed method, which Hardiyatmo (2008) introduced, was developed from the pavement of the *Sistem Cakar Ayam Modifikasi* (CAM) by changing the cylindrical foundation with short micro piles. The new system is called the nailed-slab system. Hardiyatmo (2008) conducted several studies on a nailed slab under dynamic loads, and studies on vertical loadings were done by Hardiyatmo (2009; 2011a), Nasibu (2009), Dewi (2009), Taa (2010), Somantri (2013), and Puri et al. (2011a; 2011b; 2012a; 2012b; 2013a; 2013b; 2013c; 2013d). Hardiyatmo (2011a) proposed an analysis method for determining the additional modulus of subgrade reaction. The additional modulus of subgrade reaction is the additional modulus developed by a pile. Meanwhile, the modulus of subgrade reaction is the modulus considered from a slab. Puri et al. (2012a) modified the Hardiyatmo method by considering the tolerable deflection or allowable deflection of a pavement slab (δ_a) as an approach to safety construction. This modified method has good validation (Puri et al., 2013c).

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Hardiyatmo (2011a) used the displacement factor for determining the additional modulus of subgrade reaction. The displacement factor is the ratio of the relative displacement between piles and soils (δ_0) and the pile head settlement (δ_p). The pile head settlement is assumed to be similar to the slab deflection (δ_s). The inverse of the displacement factor is the ratio of δ/δ_0. Hardiyatmo (2011b) developed the curve of the δ/δ_0 ratio based on the full-scale test of a single pile in stiff clay. The pile and slab were connected by bolts. In this paper, the curve of the δ/δ_0 ratio based on a full-scale test of a single-pile nailed slab in soft clay is developed. The pile and slab were connected monolithically. The curve of the δ/δ_0 ratio is also presented as the curve of the displacement factor. Validation based on the single-pile nailed slab will be explained.

The analytical approach in determining the equivalent modulus of subgrade reaction (k') is given as follows (Hardiyatmo, 2011a; Dewi, 2009; Puri et al., 2012a):

$$k' = k + \Delta k \quad (1)$$

where k is the modulus of subgrade reaction from plate load test (kN/m^3) and Δk is the additional modulus of subgrade reaction due to pile installation under slab (kN/m^3). The modulus of subgrade reaction from a plate load test (k) is usually taken by using a circular plate, and it should be corrected to the slab shape of the nailed slab. The secant modulus is recommended. Hardiyatmo (2011a) proposed Equation 2 in determining the additional modulus of subgrade reaction (Δk). The relative displacement between the pile and soil is considered.

$$\Delta k = \frac{\delta_0 A_s}{\delta_s^2 s^2}\left(a_d c_u + p_0 K_d \tan\varphi_d\right) \quad (2)$$

where δ_0 is the relative displacement between pile and soil (m), δ_s is the deflection of surface of slab (m), A_s is the surface area of pile shaft (m^2), s is the pile spacing (m), a_d is the adhesion factor (non-dimensional), c_u is the undrained cohesion (kN/m^2), p_o' is the average effective overburden pressure along pile (kN/m^2), K_d is the coefficient of lateral earth pressure in pile surroundings (non-dimensional), and ϕ_d is the soil internal friction angle (degree).

Hardiyatmo (2011b) re-published the relation between δ_0/δ_s and slab deflection for a full-scale model (Figure 1) while the pile and slab were connected by a bolt. The pile diameter was 20 cm, and the length of the pile varied between 1.0 m and 2.0 m.

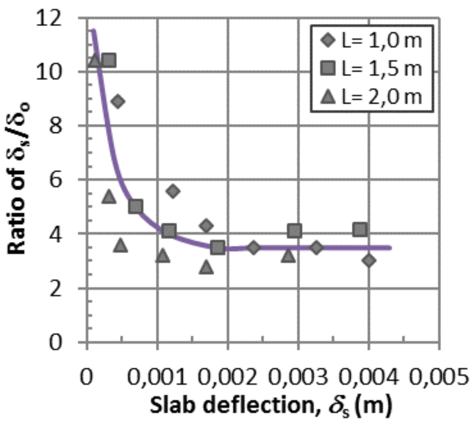


Figure 1 Relationships of δ_s/δ_0 ratio vs. slab deflection (Hardiyatmo, 2011b)

In the case of the nailed-slab system, the relative displacement between the pile and soil is difficult to define. Puri et al. (2012a) obtained Equation 3 to calculate the additional modulus of subgrade reaction, which considered the tolerable deflection of a rigid pavement slab (δ_a).

$$\Delta k = \frac{0.4 f_s A_s}{\delta_a A_{ps}} \tag{3}$$

where δ_a is the tolerable deflection of rigid pavement slab (m), f_s is the ultimate unit friction resistance of pile shaft (kN/m^2), and A_{ps} is the area of slab zone supported by single pile (m^2).

This equation did not yet consider differential settlement. The maximum differential settlement that a concrete pavement can tolerate may be expressed in terms of angular distortion or the allowable strain in the concrete. Equation 3 is already validated based on the full-scale test with good results (Puri et al., 2013c). With a nailed slab resting on soft soils, the ignored end-bearing resistance of the pile should be considered.

2. TESTING INVESTIGATION

2.1. Soil Pond, Materials, and Dimensions of Single-pile Nailed Slab

The research study on the nailed slab was conducted on soft clay. A soil pond with a width of 6m×3.7m and a depth of 2.5 m was filled with soft clay. The two longer sides were retained by masonry walls and supported by a temporary girder. An anchorage system was built near the pond. Separator sheets were set on the pond walls and on the base to avoid the effects of the surrounding soils. Soft clay taken from the District Ngawi, East Java, Indonesia, was used to fill the pond to a depth of 2.15 m. The soft clay's properties are presented in Table 1, which Puri et al. (2013c) already published. The slab and pile were reinforced concrete. The concrete strength of the slab and pile were 29.2 MPa and 17.4 MPa, respectively.

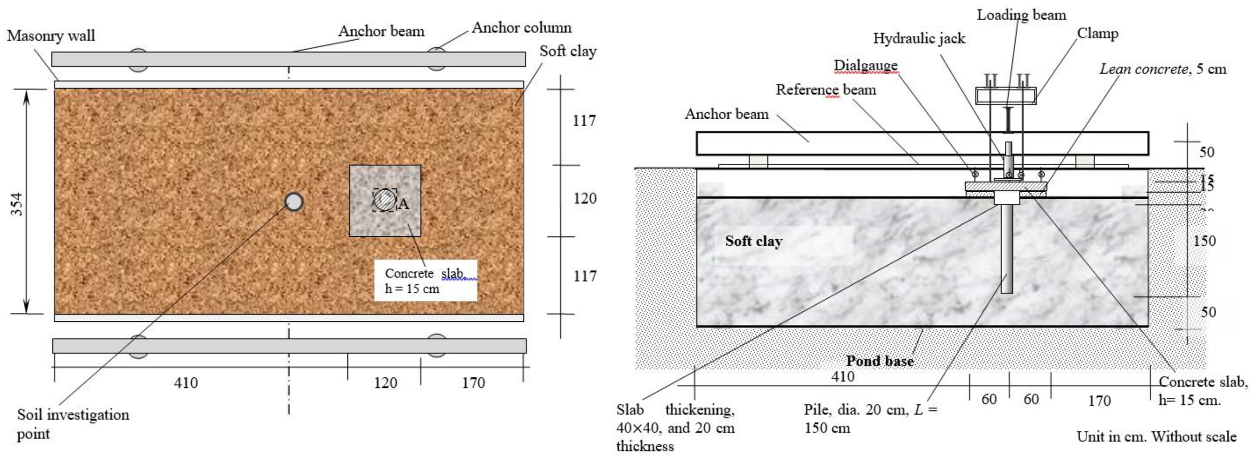
The dimensions of the nailed slab were 1.20m×1.20m, and 0.15 m in slab thickness (Figure 2), and the slab was stiffened by installing micro piles underneath it. The micro piles' dimensions were 0.20 m in width and 1.50 m in length. The pile was installed under the slab and connected monolithically by using thickening slab connectors (0.40m×0.40m and 0.20 m in thickness). There was a 5-cm lean concrete thickness under the slab.

2.2. Testing Procedures

The steps in the construction of a nailed slab can be briefly described as follows: The pond was filled with soft clay until the soil thickness reached 2.15 m (a detailed procedure was desribed in Puri et al., 2013c). The soft clay was spread to about 15 cm in thickness per layer with controlled water content (about 55%), and then, it was compacted by three passings of manual compaction. Some soil investigations were conducted, i.e., soil boring, vane shear test, CBR test, and plate load test. After that, a pile was driven by the pre-drilled method and then continued via hydraulic jacking until the pile top reached the design level. The pile was tested for compression-bearing capacity and tension capacity. The pile compression test was loaded by a hydraulic jack via a circular plate with 20 cm in diameter (same as the pile diameter). The pile tension test was loaded by a hydraulic jack via a loading yoke on the pile head. The yoke was put on the pile hook that was welded on the pile head. Soil was excavated for the thickening of the slab. The 5-cm lean concrete was then poured onto the soil surface. The slab reinforcement rebar was assembled. Then, concrete was poured for the slab. The slab was cured by using a wet carpet, and when the concrete age was 28 days, the loading setup was assembled. The loading test was conducted on the slab for different load positions. Loads were transferred to the slab surface by a hydraulic jack via a circular plate that was 30 cm in diameter (the plate represents the single-wheel load contact area). The loading position was centric of the slab. Then, the deflections on the slab were recorded by using a dialgauge. Deflections were observed for every corner and center of the slab surface. Some photographs in construction and testing were presented in Figure 3. The test for the slab alone was done by using a similar procedure but without slab thickening. The slab thickness was the same as that of the single-pile nailed slab.

Table 1 Soft clay properties (Puri et al., 2013c)

No.	Parameter	Unit	Average
1.	Specific gravity, G_s	-	2.55
2.	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
3.	Water content, *w*	%	54.87
4.	Fines content	%	92.93
5.	Sand content	%	6.89
6.	Bulk density, γ	kN/m^3	16.32
7.	Dry density, γ_d	kN/m^3	10.90
8.	Undrained shear strength, s_u		
	- Undisturbed	kN/m^2	20.14
	- Remolded	kN/m^2	11.74
9.	CBR	%	0.83
10.	Soil classification:		
	- AASHTO	-	A-7-6
	- USCS	-	CH



(a) (b)

Figure 2 Schematic diagram of testing investigation: (a) plan view; (b) cross section and loading equipment

(a) (b)

Figure 3 Photographs of investigation on single-pile nailed-slab system: (a) slab reinforcement; (b) loading test

2.3. Develop the Curve of Displacement Factor

The curve of the displacement factor will be developed by using the Hardiyatmo method. The displacement factor is the ratio between the relative displacement between the pile and soil and the displacement of the pile head (Hardiyatmo, 2011a). This factor is

$$\alpha = \frac{\delta_0}{\delta_p} \tag{5}$$

The δ_p is the displacement of the pile head (m). Because the soft clay is considered, the term of $p_0K_d\tan\phi_d = 0$, and Equation 2 can be re-arranged as Equation 6.

$$\frac{\delta_0}{\delta_s} = \frac{\Delta k \delta_s A}{A_s a_d c_u} \tag{6}$$

To find the displacement factor, Equation 6 is used by assuming that the displacement of the pile head is equal to the displacement of the slab surface.

An analysis of the deflection was calculated by the theory of beams on elastic foundation (BoEF). This method could be used to calculate the deflections due to the load acting on the plate-supported piles (Hardiyatmo, 2009, 2011a; Taa, 2010; Puri et al., 2011b, 2012a). They used Hetenyi's formulas (1974). The deflection of the finite length of the beam resting on an elastic foundation was considered due to a single concentrated load. The modulus of subgrade reaction, *k*, is replaced by *k'* in Equation 1 for the analysis of the nailed-slab system. BoEFW simple software is used to analyze slab deflections.

3. RESULTS AND DISCUSSION

3.1. Single-pile Loading Test

Figure 4 shows the results of the loading tests. Testing was conducted after 30 days of pile driving. For the loading test, the single pile did not reach a failure condition until it reached the beginning of the plastic zone. Pile axial compression-bearing capacity is 28 kN and has linear elastic behavior up to 25 kN (Figure 5a). Tension-bearing capacity is 20 kN (Figure 4b). The relationship between unit friction (based on the pile tension test) and displacement is shown in Figure 4c. The ultimate unit friction f_{su} is 21.21 kPa at a displacement of 0.715 mm. The unit friction was corrected to a pile weight (1.13 kN) and loading yoke weight (0.18 kN).

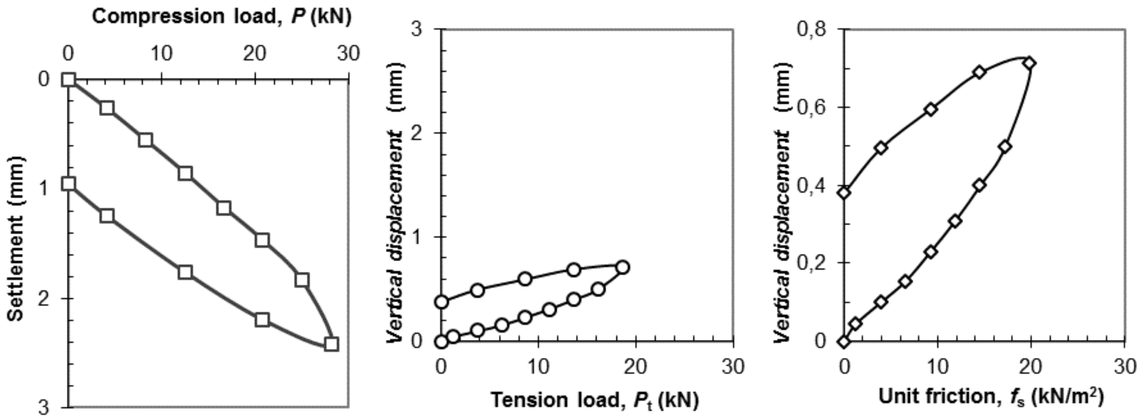


Figure 4 Single-pile test results: (a) axial compression; (b) axial tension; (c) pile unit friction

3.2. Loading Test Results of Slab and Single-pile Nailed Slab

Figure 5 shows the P-δ relationship for both tests. The installed pile under the slab reduced slab settlement and increased the bearing capacity of the structure. The elastic condition reached about 25 kN and 30 kN for the slab alone and the nailed slab, respectively. However, the nailed slab is stiffer than the slab alone is.

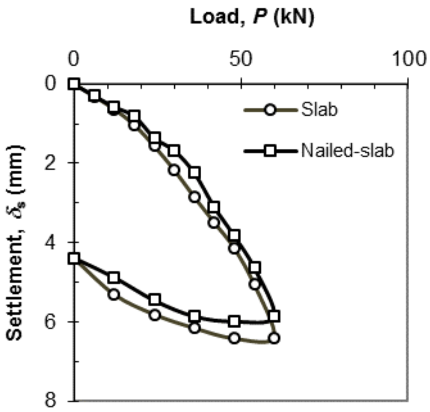
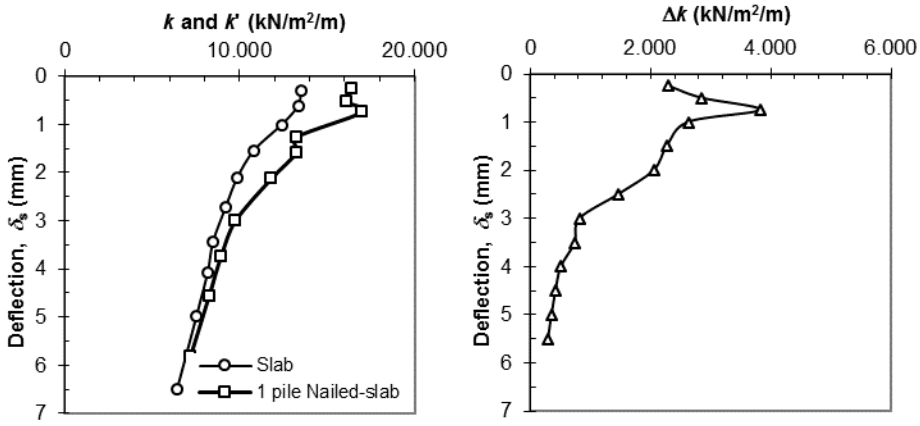


Figure 5 P-δ relationship for loading tests of slab and single-pile nailed slab

3.3. Curve of Displacement Factor α (ratio of δ_0/δ_s)

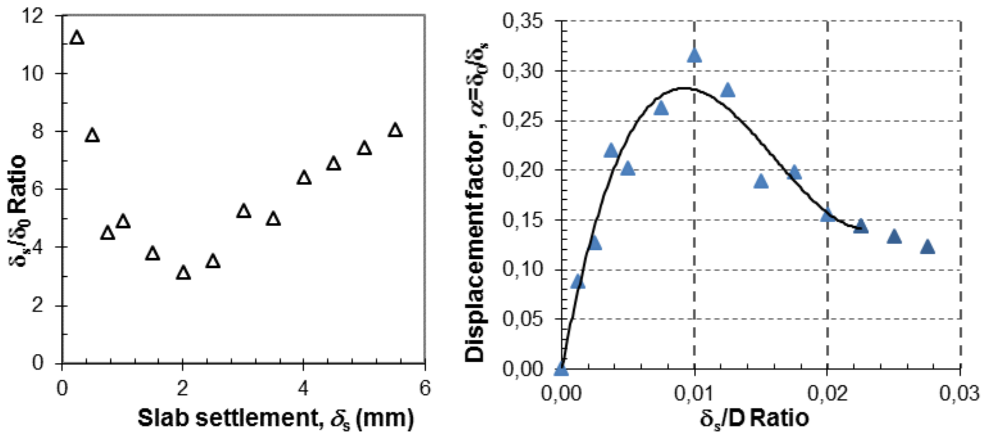
Based on the loading tests of the slab and single-pile nailed slab, the modulus of subgrade reaction was calculated for the slab alone (k) and for the nailed slab (k'). The additional modulus of subgrade reaction for the nailed slab (Δk) was defined. Those moduli are presented in Figure 6 and will be used for calculating the slab deflection by using Hardiyatmo's formula (2011a).

The ratio of δ_s/δ_0 was calculated by using Equation 6, and the additional modulus of subgrade reactions Δk (as presented in Figure 6) were used. For soft clay, the $p_0 K_d \tan\phi = 0$. Then, the displacement factor (δ_0/δ_s) was taken by inversing the δ_s/δ_0 ratio. For the dimensions of the pile, the pile area A = 1.44 m^2, and the pile skin area A_s = 1.07 m^2. The $a_d c_u = f_s$ was determined based on Figure 5c. The δ_s/δ_0 ratio for the single-pile nailed slab could be determined, and the calculated results are present in Figure 7a. This figure shows the distribution of the δ_s/δ_0 ratio. This curve is similar to that in Figure 1, especially for the pile length of 1.5 m and 2.0 m, where the δ_s/δ_0 ratio decreases to a displacement of 2 mm and then tends to increase after this displacement. For general purposes, Figure 7a is presented as Figure 7b (curve of the displacement factor) and is related to the δ_s/D ratio. D is the pile diameter. The δ_0/δ_s ratio has a maximum value at the maximum displacement of 2 mm (δ_s/D = 0.10).



(a) (b)

Figure 6 Modulus of subgrade reaction: (a) distribution of k and k'; (b) modulus Δk



(a) (b)

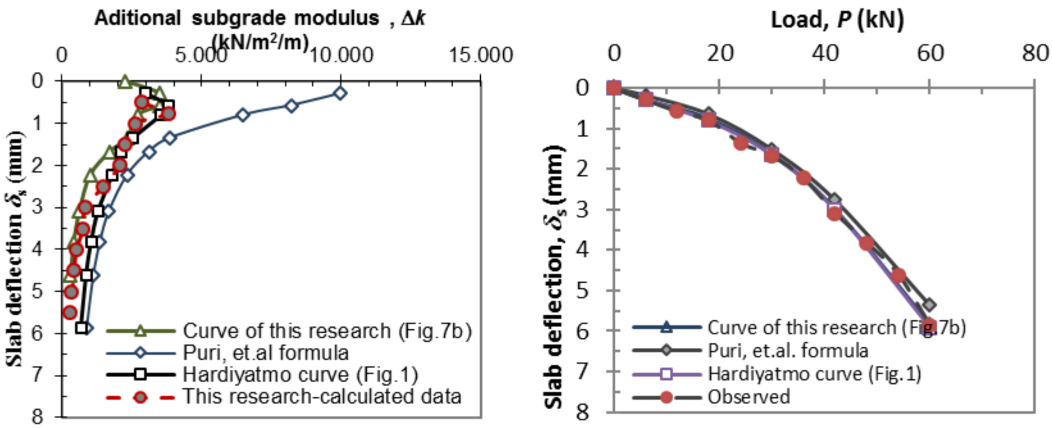
Figure 7 Curve for single-pile nailed slab: (a) δ_s/δ_0 vs. δ_s; (b) curve of δ_0/δ_s

The mechanism of the relative displacement between soils and the pile (δ_0) is related to the slab deflection (δ_s). The δ_0 is not directly mobilized at the beginning of the slab deflection's occurrence. It will begin to take place in the curtain of the slab deflection. The δ_0 is smaller than the slab deflection at the beginning of the loading; hence, the α is small. Because the load is increased, the δ_s increases and δ_0 increases until the maximum value is reached. Hence, α tends to increase until the maximum value. Then, increasing the slab deflection makes the soils and pile move simultaneously with the slab. It causes the α to decrease to zero (at least the asymptote to the δ_s axis) because the δ_0 reaches the maximum, whereas the δ_s goes in the direction.

3.4. Slab Deflection

The additional modulus and equivalent modulus of subgrade reaction are shown in Figure 8a. The unit friction f_s takes the ultimate value (21.21 kPa) for deflection > 0.7 mm. The k value is taken from Figure 6 by the interpolating method for appropriate deflection. It is shown that all methods are in good agreement with the observation. Figure 8b shows that the use of Hardiyatmo's curve and this research curve (Figure 7b) produces deflection results that are in good agreement with the observation, even though it is a little bit underestimated. The calculated deflection based on Puri et al.'s (2012a) formula is also in good agreement with the observation, even though it is more underestimated. Figure 8b shows that the use of Hardiyatmo's curve and this research curve (Figure 7b) produces deflection results that are in good agreement with the observation, even though it is a little bit underestimated. The calculated deflection based on Puri et al's (2012a) formula is also in good agreement with the observation, even though it is more underestimated.

In the Puri et al. (2012a) formula, the observed deflections were used as tolerable deflections. In the case where the tolerable deflection is determined to be 5 mm, then the Δk = 1,109.87 kN/m^2/m, and k' = 7,988.19 kN/m^2/m. According to Figure 8a (Puri et al., 2012a formula), the overestimated deflection for a load less than 60 kN is obtained. It is caused by a k' lower than that in Figure 8a. It can be concluded that the use of defined tolerable deflection will produce calculation results in a safer zone. All calculated deflections are underestimated. However, using figures 1 and 7b gives the smallest differentiation in the averages of -0.66% and -2.54%, respectively, whereas the Puri et al. (2012a) formula is sufficient enough (average differentiation of -17.89%). In this case, the Poisson's ratio did not influence the slab deflections. The BoEF analysis is in two dimensional (2D). In fact, 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 Figure 7b will be on the safety zone.



(a) (b)

Figure 8 (a) The Δk - δ relationship based on several methods; (b) the P-δ

4. CONCLUSION

According to the results and discussion, it can be concluded that the installed piles under the slab contribute to increasing the modulus of subgrade reaction, which is represented by the additional modulus of subgrade reaction. The equivalent modulus of subgrade reaction of the single-pile nailed slab on soft clay was about 1.14 times the modulus of subgrade reaction of the slab alone. Puri et al.'s (2012a) formula, expressed as Equation 3 and the curve of the displacement factor from this research (Figure 7b), is useful for estimating the additional modulus of subgrade reaction. Calculated deflections based on these methods were in good agreement with the observation. Hence, they can be used in preliminary design. For further research, an additional modulus of subgrade reaction for the edge load should be developed in conjunction with the idea that edge loads can cause critical loading.

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