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VALIDATION THE CURVE OF DISPLACEMENT FACTOR DUE TO FULL SCALE OF ONE PILE ROW NAILED-SLAB PAVEMENT SYSTEM

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ABSTRACT: A proposed alternative solution for rigid pavement problem on soft soils is pavement of Nailed-slab System. It is a kind developing of rigid pavement. Equivalent modulus of subgrade reaction (*k*') can be used to analyze Nailed-slab System. This modulus consists of the modulus of sub grade reaction from plate load test (*k*) and additional modulus of sub grade reaction due to pile installing (Δk). The Δk can also be determine by using the curve of displacement factor. This research is aimed to validate the theory of additional modulus of sub grade reaction by using the curve of displacement factor due to the results of prototype test of Nailed-slab with 1 pile row. The prototypes were constructed on soft clay and the connection between pile and slab was perfect monolithically. These systems were loaded by monotonic loads. Calculated deflections based on method of the additional modulus of sub grade reaction were compared to the observed deflection and the results from Finite Element Method. Result shows in good agreement with the observation. Into the bargain the proposed method of analysis was practical in use and timeless consuming. Designing the Nailed-slab by considering single pile row which used *k*' will result a design in safety zone.

Keywords: Nailed-slab system, soft clay, sub grade modulus, deflection, rigid pavement, displacement factor

1. INTRODUCTION

The pavement of Nailed-slab System was developed by changing the shell of pavement of chicken foot system (*Sistem Cakar Ayam*) with short piles in order to gain the efficiency of construction implementation [1].The Nailed-slab System is not a kind of soil improvement althought it is proposed to be applicable for soft soils [2]. This system is a kind of construction to increase the performance of rigid pavement on soft soils. This system consists of a thin pile cap that also serves as a rigid pavement, and short piles attached underneath. The composite system (consists of piles, slab, and soils surrounding the piles) is expected to be formed to bear the loads. The mainly function of pile is as a nail to the slab so that the slab remains in contact with the subgrade. The installed piles under the slab also increase the slab stiffness [3]. Then the slab thickness can be decreased. The decreasing of slab thickness can reduce the weight of the structure and will be beneficial for soft soils [4]. Hence, a more durable pavement can be acquired with the result that the pumping could not take place and differential settlement could be reduced. Yet the consolidation problem of soft soils under the construction is not covered by the nailed-slab. This system was recommended the thin pile cap (thickness about 12 cm to 25 cm) and short micro piles installed under the pavement slab. Micro piles have 12 cm – 20 cm in diameter, 1 m – 2 m length, and 1 m – 1.5 m pile spacing.

Hardiyatmo [1] conducted several studies on a nailed slab under dynamic loads, and studies on vertical loadings for soft clay were done by Hardiyatmo ([5], [6]), and Puri et al. ([3], [7], [8], [9], [10], [11], [12]), and for stiff lay by Nasibu [13], and Dewi [14]. Physical modeling of nailed-slab also conducted on expansive clay by Taa [15] and Diana, et.l ([16], [17]), and Somantri [18] and Waruwu [19]for sand and peat soil respectively. Nailed-slab System due to tension loading was studied by Puri, et.al. [20] and Puri [21].

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Design method by using equivalent of subgrade reaction (*k*') in Nailed-sla analysis was proposed by Hardiyatmo modulus consists of the modulus of s reaction from plate load test (k) and additional modulus of sub grade reaction due to pile installing (Δk). Analysis method in determining the additional modulus of subgrade reaction was also proposed by Hardiyatmo [6]. And it was modified by Puri, et.al. [8] by consider the tolerable deflection or allowable deflection of pavement slab as an approach of safety construction and has good validation due to full scale test [12].

Additional modulus of sub grade reaction considered displacement factor [6]. This factor is the ratio of the relative displacement between piles and soils (δ_0) and the pile head settlement (δ). The inverse of displacement factor is the ratio of δ/δ_0. The curve of δ/δ_0 ratio was developed by Hardiyatmo [22] based on full scale test of single pile Nailed-slab in stiff clay. The pile and slab was connected by bolts. Puri [23] developed curve of displacement factor ($\alpha=\delta_s/\delta_0$) based on full scale test on single pile Nailed-slab in soft clay. Pile and slab was connected perfect monolithically. It was good validated to full scale of single pile Nailed-slab. The application of this curve on the full scale Nailed-slab with 1 row of piles will be discussed in this paper.

2. THEORITICAL BACKGROUND

2.1 Equivalent Modulus of Sub Grade Reaction

The analytical approach in determining equivalent modulus of sub grade reaction (k') is given as follows ([6], [14], [8]):

$$k' = k + \Delta k \tag{1}$$

Where k : modulus of sub grade reaction from plate load test (kN/m^3), Δk: additional modulus of subgrade reaction due to pile installing under slab (kN/m^3).

Considering the soil bearing pressure under an individual nailed-slab system, Hardiyatmo [6] proposed Eq. (2) in determining the additional modulus of sub grade reaction (Δk). The relative displacement between pile and soil is considered.

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

Where δ_0 : relative displacement between pile and soil (m), δ : deflection of surface of plate (m), A_s : surface area of pile shaft (m^2), s : width area of slab (m), a_d: adhesion factor (non-dimensional), c_u: undrained cohesion (kN/m^2), p_o': average effective over burden pressure along of pile (kN/m^2), K_d: coefficient of lateral earth pressure in pile surroundings (non-dimensional), ϕ_d: soil internal friction angle (degree).

The relation between δ_0/δ and slab deflection from pile model with a 4 cm diameter is also given by Hardiyatmo [6]. Hardiyatmo [22] re-published the relation between δ_0/δ and slab deflection for full scale model while the pile and slab was connected by bolt. The pile diameter was 20 cm dan the length of pile was varied between 1.0 m to 2.0 m. Puri [23] used invers of ratio of δ_s/δ_0 that is called displacement factor and presented in Figure1. Then, Eq.(2) can be re-written as follows

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

Where δ_a: tolerable deflection of rigid pavement slab (m). The curve of displacement factor is presented in Figure 1. Puri [24] also developed the curve of displacement factor for stiff clay based on Hardiyatmo [6].

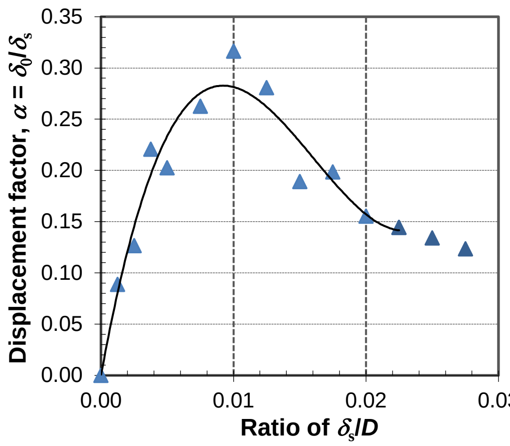


Figure 1 Correlation of displacement factor ($\alpha = \delta_0/\delta_s$) and ratio of δ_s/D for softclay [23]

For designing purposes, the relative displacement between pile and soil is difficult to define. Puri, et.al. [8] obtained Eq. (4) to define the additional modulus of sub grade reaction which considered the tolerable deflection of rigid pavement slab (δ_a). This approach is called Modified Hardiyatmo method.

$$\Delta k = \frac{0.4 f_s A_s}{\delta_a A_{ps}} \tag{4}$$

Where δ_a : tolerable deflection of rigid pavement slab (m), f_s: ultimate unit friction resistance of pile shaft (kN/m^2), A_s : surface area of pile shaft (m^2), A_{ps} : area of plate zone which supported by single pile (m^2).

Additional modulus of subgrade reaction for Nailed-slab in soft clay is expressed by

$$\Delta k = \frac{0.4 a_d c_u A_s}{\delta_a A_{ps}} \tag{5}$$

Where a_d: adhesion factor (non-dimensional), c_u: undrainedcohesion (kN/m^2).

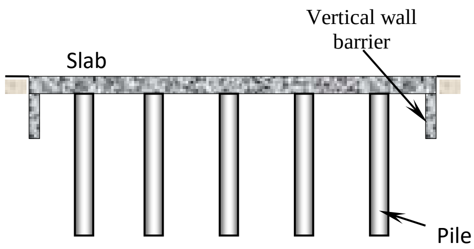
The modulus of sub grade reaction from the plate load test (k) is usually taken by using circular plate, and it should be corrected to slab shape of the nailed-slab.

2.2 Analysis of Deflection

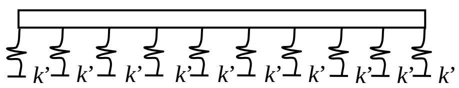
Analysis of deflection of a nailed-slab by using equivalent modulus of subgrade reaction has been done by Hardiyatmo ([5], [6]), Puri, et.al. ([7], [8], [9], [10], [11]), Somantri [18] and Puri ([2], [23]). This modular was also implemented in cakar ayam analysis ([25], [26], [27]). In this paper the deflection will be analyzed by using Beam on

Elastic Foundation (BoEF) and finite element method (FEM). The theory of BoEF can be used to calculate the deflections due to the load acting on plate-supported piles ([5], [6], [15], [7], [8], [10], [20]). They used the Hetenyi's formulas. In this paper the Roark's formulas will be used. The deflection of the finite length of the beam resting on an elastic foundation due to a single concentrated load at any point is explained by using Roark's formulas in [28].

Figure 2 shows the approach model of Nailed-slab System for BoEF analysis. Figure 2a is represented the real construction and Figure 2b is represented the approach model. Vertical wall barriers on the both end of slab are neglected since BoEF cannot accommodate them. Piles are modelled by *k*' springs. In BoEF analysis, the k_0 value is changed by *k*' value which calculated by Eq.(1). Total deflection on the observed point is defined by superposition method of deflection caused by concentrated load and moment.



a. Real construction



b. Approach model

Figure 2 Approach model of Nailed-slab analysis in BoEF (vertical wall barriers are neglected) [2]

FEM analysis will use the commercial 2D Plaxis software. Nailed-slab will be analyzed by plain strain analysis. Pile will be transformed to continuous wall element by an equivalent thickness on plain strain geometry. Wall thickness will be calculated according to the ratio of pile section area to soil area which kept constant.

3. TESTING INVESTIGATION

This testing investigation was explained by Puri, et.al ([11], [29]) except for 1-pile row Nailed-slab and here is re-explained.

3.1 Soil Pond and Materials

Nailed-slab will be conducted on soft clay. A 6 m x 3.7 m soil pond was conducted by digging the existing soil until the depth of 2.5 m. On the 2 longer side was retained by masonry walls and supported by some temporarily girder. The anchorage system was built near the pond. Separator sheets were set on the pond walls and base to avoid the effects of surrounding existing soils. A 2.15 m of depth of test box was filled by soft clay which taken from District Ngawi, East Java, Indonesia. The soft clay properties are presented in [11] and [12]. There was soft cpay with plasticity index 59.98% and undrained shear strength 20.14 kN/m^2. The slab and piles were reinforced concrete. The concrete strength characteristic of slab and piles were 29.2 MPa and 17.4 MPa respectively.The flexural strength of the slab was 4,397.6 kPa. The coefficien of subgrade reaction based on standart plate load test was 15,000 kPa/m. This coefficien became 2,750 kPa/m after correction due to dimension and shape of nailed-slab (according to [30]).

3.2. Dimension of Nailed-slab

Test on 1 pile row Nailed-slab consisted of slab with 600 cm × 120 cm × 15 cm in dimension. Pile length was 150 cm and pile spacing was 120 cm. This model was obtained by cutting the 600 cm ×354 cm × 15 cm Nailed-slab became 3 parts where each part consisted of one pile row. The tested 1 pile row Nailed-slab was the middle one with slab dimension 600 cm × 120 cm × 15 cm as shown in Figure 3.

3.3. Testing Procedures

The steps in construction of Nailed-slab can be briefly described as follows: the pond was filled by soft clay until the soil thickness reach 2.15 m. Soft clay was spread about 15 cm in thickness per layer with controlled water content, and then it was compacted by 3 passing of manual compaction. Each soil layer thickness was decreased to about 10 cm per layer. Soft clay was cured by covering its surface with plastic sheet and wet carpet. 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 pre-drilled method and then continued by hydraulic jacking until the pile top reach the design level.

The pile was tested for compression bearing capacity and tension capacity. Soil was excavated for thickening slab. The 5 cm lean concrete then poured on the soil surface, and continued by conducting CBR test and plate load test after 3 days. The slab and vertical wall barrier reinforcement rebar were assembled. And then concrete was poured for slab. Slab was cured by wet carpet and after 28 days of concrete age the loading set up was assembled. Loading test was conducted on the slab for different load positions

(Point A and C in Figure 3a). Loads were transfer to the slab surface by using circular plate with 30 cm in diameter (the plate represents the single wheel load contact area). Then the instrumentations were recorded. Some photographs in construction and testing were presented in Figure 4.

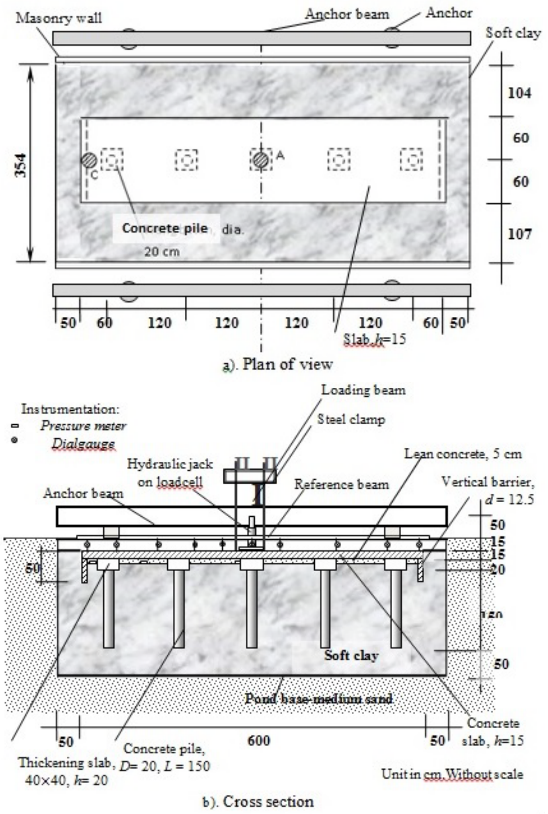


Figure 3 Schematic diagram of full scale Nailed-slab with 1 pile row [2]

3.4. Analysis Method

Numerical analysis will be conducted by using BoEF Analysis version 1.4 and 2D Plaxis v. 8.6.

Piles and soils were approached by vertical spring *k'* in BoEF analysis. In 2D Plaxis FEM (plain strain analysis), the soft clay was modeled by Mohr-Coulomb in un-drained condition. All structural elements were modeled by plate element in linear-elastic behavior. Lean concrete was modeled by soil with linear-elastic non-porous material. All structural elements were modeled by linear-elastic behavior. This 2D FEM used plain strain analysis type. Soil parameters and idealization of structural elements are presented in Table 1 and 2 respectively. The thickening slab was ignored since it could not be modeled by Plaxis 2D.

Figure 4 Photographs of loading tests on full scale Nailed-slab with 1 pile row (point C)

4. RESULTS AND DISCUSSIONS

4.1. The 2D Numerical Analysis of 1 Pile-row Nailed-slab

Result shows that the vertical wall barrier was not significant effect (Figure 5a). Deformed mesh is shown in Figure 6 which the end of slab was uplift.

Table 1 Model and parameters of soil

Parameters	Name/ Notation	Soft clay	Sand	Unit
Material model	Model	Mohr-Coulomb	Mohr-Coulomb	-
Material behavior	Type	*Undrained*	*Drained*	-
Saturated density	γ_{sat}	16.30	18.00	kN/m^3
Dry density	γ_d	10.90	20.00	kN/m^3
Young's Modulus	E	1,790.00	42,750.00	kPa
Poisson's ratio	v	0.45	0.35	-
Undrained cohesion	c_u	20.00	1.00	kPa
Internal friction angle	ϕ	1.00	47.80	o
Dilatancy angle	ψ	0.00	2.00	o
Initial void ratio	e_0	1.19	0.50	-
Interface strength ratio	R	0.80	0.70	

Table 2 Model and parameters of structural elements in FEM 2D plain strain

Parameters	Name/ Notation	Lean concrete (LC)	Structural elements			Unit
			Slab	Vertical wall barrier	Pile	
Material model	Model	Volume element	*Plate*	*Plate*	*Plate*	-
Material behavior	Type	Elastic	Elastic	Elastic	Elastic	-
Normal stiffness	*EA*	-	4,554,000	3,795,000	616,696	kN/m
Flexural rigidity	*EI*	-	8,539	4.941	75,655	kNm^2/m
Equivalent thickness	*d*	-	0.15	0.125	0,027	m
Weight	*w*	-	3.60	3.00	29.12	kNm/m
Poisson's ratio	ν	0.2	0.15	0.15	0.20	-
Unit weight	γ	22	24	24	24	kN/m^3
Young's Modulus	*E*	17,900	25,300	25,300	19,600	MN/m^2
Interface strength ratio	*R*	0.80	0.80	0.80	0.80	-

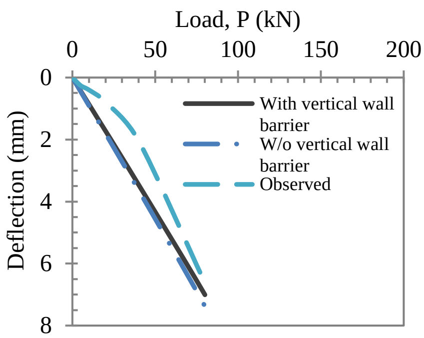
It is quite different with result in full scale test. It is concluded that the Plaxis 2D could not model the vertical wall barrier which lower position than slab level, as well as could not model the thickening slab. The distribution of deflection along the slab will be discussed in section 4.2.

Lean concrete can reduce deflection and it significant under centric load (figure 5b). Reduced deflection tends to be higher by increasing the thickness of lean concrete.

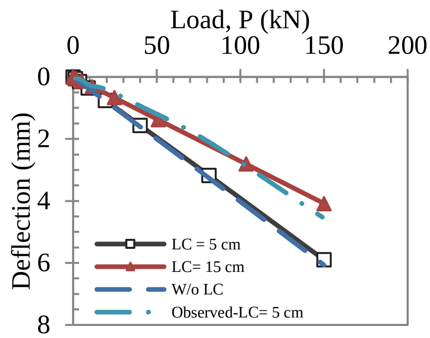
4.2. Validation the Method of Preliminary Design Based on *k'*

The structure of pavement of full scale Nailed-slab System was calculated to find deflections and internal forces by using equivalent modulus of subgrade reaction (*k'*). The soil modulus of subgrade reaction for 1.20 m slab width was 3,300 kPa/m. Calculations were run by BoEF software. Design load was 40 kN single wheel load. Table 3 gives calculating results of *k'* where calculated by using Eq.(5) and Figure 1.

Calculated results based on Eq.(5) and Figure1 were good agreement with observation (Figure7). Calculated results based on Figure1 were higher than results based on Eq.(5) on the average 13.13%. It is caused by the equivalent modulus of subgrade reaction based on Figure1 higher than based on Eq.(5). Calculated deflections based on Eq.(5) and Figure1 were higher than observation on the average 51.37% and 66.20% respectively. These over-estimated results were caused of neglected to vertical wall barrier and thickening slab. BoEF distributes a concentrated load *P* over slab width, so the working load does not concentrated load in analyzing. It is also occurred to edge loads. The calculated deflections are linear-elastic and agreed with assumption of both methods. Results from 2D FEM were very close to observations (Figure 7). However, the distributions of deflections along the slab show that there are uplifts on the ends of slab (Figure 7b and 7d), but the soil were kept in contact with the slab (Figure 6a and 6b). It is supposedly that the software could not model the vertical wall barrier.



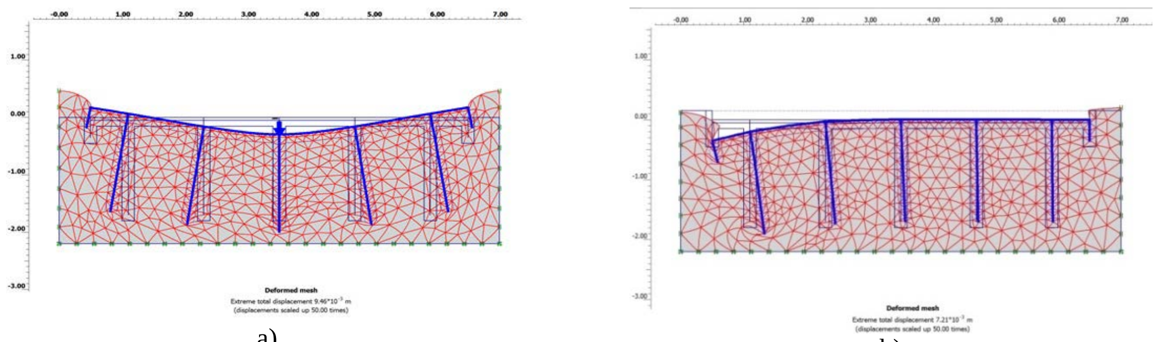
a)



b)

Figure 5 *P*-δ relationships from FEM 2D, a) Effect of vertical wall barrier for edge load on C, b) Effect of lean concrete for concentric load on A

Nailed-slab System under centric load of single wheel load (40 kN), maximum calculated deflection was 2.60 mm and it was not exceed the tolerable deflection (δ_a) = 5 mm.



a) b)

Figure 6 Deformed mesh of 1-pile row Nailed-slab, a) for concentric load on A, b) for edge load on C

Table 3 Equivalent modulus of subgrade reaction for1 pile row number

Load position	Eq. (5)			Formula Hardiyatmo and Figure 1		
	k (kN/m^3)	Δk (kN/m^3)	k' (kN/m^3)	k (kN/m^3)	Δk (kN/m^3)	k' (kN/m^3)
Centric	3,300	1,175	4,755	3,300	380	3,680
Edge	3,300	1,175	6,710*	3,300	380	5,520*

Note: * k' for edge load was multiplied by multiplying factor 1.5

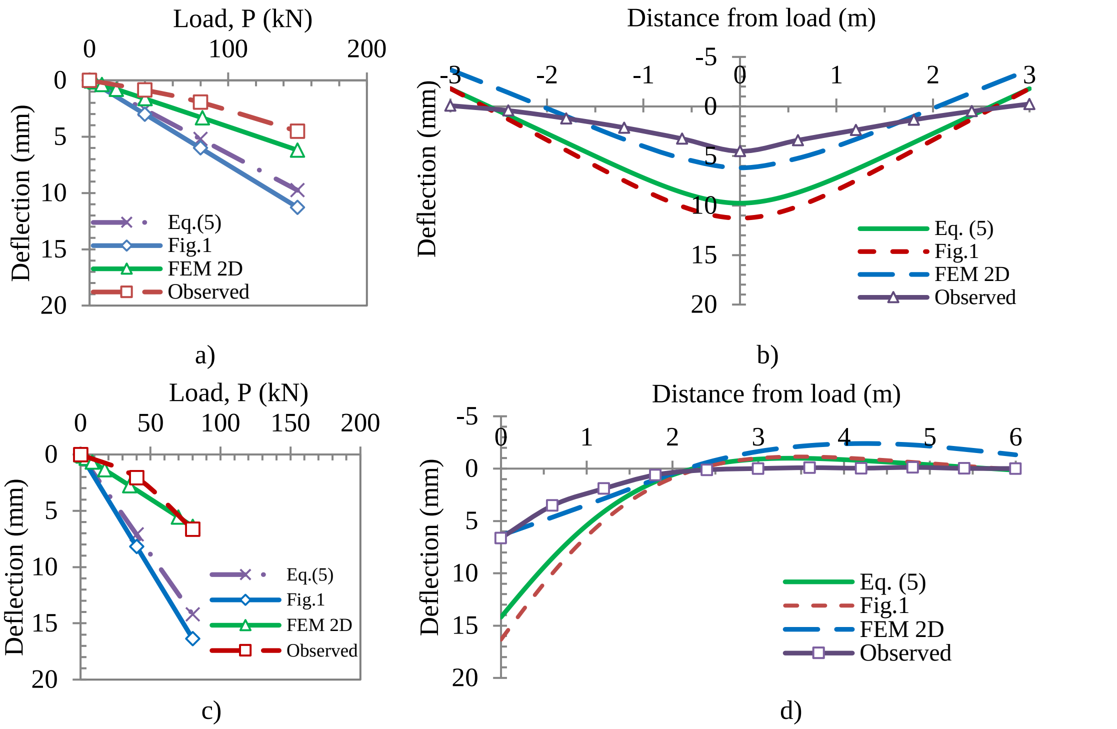


Figure 7 Calculated deflections for full scale Nailed-slab with 1 pile row; a) P-δ concentric load, b) Deflection along slab-P_{max} concentric, c) P-δ edge load, d) Deflection along slab-P_{max} edge

Maximum calculated deflection due to edge load was 7.10 mm $>\delta_a$, but then the observed deflection for centric and edge load were only 1.21 mm and 2.04 mm respectively. Building on these facts, the design of Nailed-slab System is sufficiency. And by considering that in the field the Nailed-slab will be built in great quantities of piles, then the designing based on single pile row will result a design in safety zone. Therefore, the proposed formula and designing by considering single pile row were very sufficiency and will result a design in safety zone. And so do, it is easier in conducting the analysis.

4. CONCLUSION

According to loading test results on full scale Pavement of Nailed-slab with 1 pile row, analysis results, and discussion, several important conclusions can be concluded as follows

1. The tested model and full scale Nailed-slab system on soft clay showed the smooth deflected bowl. It indicates that the all piles abled to give similar responses. Compression and pull out capacity of piles were mobilized that made the slab keep contact with soil.
2. Based on observation, the system has higher stiffness to bear the loads. It was evidenced by linear elastic-response until load 80 kN. The higher stiffness of the system was experienced by small deflection about 2 mm due to centric load (P = 80 kN ≈ 2xsingle wheel load).
3. Installed piles under the slab which embedded into the soils were increase slab stiffness. It could be expressed by Δk. Such was the case that increasing in pile row number could increase the stiffness of the system which represented by k'.
4. Formula and curve of displacement factor for determining the additional modulus of subgrade reaction could be used for analyzing the Nailed-slab System. Both were validated by observation, BoEF analysis and 2D FEM. Analysis results were good agreement with observation, although tends less satisfy for edge loads. Employing k' in BoEF analysis was sufficiency enough. Into the bargain the proposed method of analysis was practical in use and timeless consuming. Designing the Nailed-slab by considering single pile row which used k' will result a safety design.

5. ACKNOWLEDGEMENTS

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VALIDATION THE CURVE OF DISPLACEMENT FACTOR DUE TO FULL SCALE OF ONE PILE ROW NAILED-SLAB PAVEMENT SYSTEM

This title needs to be improved; notto standard to give such a title

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ABSTRACT: A proposed alternative solution for rigid pavement problem on soft soils is pavement of Nailed-slab System. It is a kind developing of rigid pavement. Equivalent modulus of subgrade reaction (*k*') can be used to analyze Nailed-slab System. This modulus consists of the modulus of sub grade reaction from plate load test (*k*) and additional modulus of sub grade reaction due to pile installing (Δk). The Δk can also be determine by using the curve of displacement factor. This research is aimed to validate the theory of additional modulus of sub grade reaction by using the curve of displacement factor due to the results of prototype test of Nailed-slab with 1 pile row. The prototypes were constructed on soft clay and the connection between pile and slab was perfect monolithically. These systems were loaded by monotonic loads. Calculated deflections [illegible] grade reaction were compared to the observed defl[illegible] result shows in good agreement with the observation. Into the bargain the proposed method of analysis was practical in use and timeless consuming. Designing the Nailed-slab by considering single pile row which used *k*' will result a design in safety zone.

improve this abstract; many english mistakes; notreading smoothly

Keywords: Nailed-slab system, soft clay, sub grade modulus, deflection, rigid pavement, displacement factor

1. INTRODUCTION

The pavement of Nailed-slab System was developed by changing the shell of pavement of chicken foot system (*Sistem Cakar Ayam*) with short piles in order to gain the efficiency of construction implementation [1].The Nailed-slab System is not a kind of soil improvement althought it is proposed to be applicable for soft soils [2]. This system is a kind of construction to increase the performance of rigid pavement on soft soils. This system consists of a thin pile cap that also serves as a rigid pavement, and short piles attached underneath. The composite system (consists of piles, slab, and soils surrounding the piles) is expected to be formed to bear the loads. The mainly function of pile is as a nail to the slab so that the slab remains in contact with the subgrade. The installed piles under the slab also increase the slab stiffness [3]. Then the slab thickness can be decreased. The decreasing of slab thickness can reduce the weight of the structure and will be beneficial for soft soils [4]. Hence, a more durable pavement can be acquired with the result that the pumping could not take place and differential settlement could be reduced. Yet the consolidation problem of soft soils under the construction is not covered by the nailed-slab. This system was recommended the thin pile cap (thickness about 12 cm to 25 cm) and short micro piles installed under the pavement slab. Micro piles have 12 cm – 20 cm in diameter, 1 m – 2 m length, and 1 m – 1.5 m pile spacing.

Hardiyatmo [1] conducted several studies on a nailed slab under dynamic loads, and studies on vertical loadings for soft clay were done by Hardiyatmo ([5], [6]), and Puri et al. ([3], [7], [8], [9], [10], [11], [12]), and for stiff lay by Nasibu [13], and Dewi [14]. Physical modeling of nailed-slab also conducted on expansive clay by Taa [15] and Diana, et.l ([16], [17]), and Somantri [18] and Waruwu [19]for sand and peat soil respectively. Nailed-slab System due to tension loading was studied by Puri, et.al. [20] and Puri [21].

Design method by using equivalent modulus of subgrade reaction (*k*') in Nailed-slab System analysis was proposed by Hardiyatmo [5]. This modulus consists of the modulus of sub grade reaction from plate load test (k) and additional modulus of sub grade reaction due to pile installing (Δk). Analysis method in determining the additional modulus of subgrade reaction was also proposed by Hardiyatmo [6]. And it was modified by Puri, et.al. [8] by consider the tolerable deflection or allowable deflection of pavement slab as an approach of safety construction and has good validation due to full scale test [12].

Additional modulus of sub grade reaction considered displacement factor [6]. This factor is the ratio of the relative displacement between piles and soils (δ_0) and the pile head settlement (δ). The inverse of displacement factor is the ratio of δ/δ_0. The curve of δ/δ_0 ratio was developed by Hardiyatmo [22] based on full scale test of single pile Nailed-slab in stiff clay. The pile and slab was connected by bolts. Puri [23] developed curve of displacement factor ($\alpha=\delta_s/\delta_0$) based on full scale test on single pile Nailed-slab in soft clay. Pile and slab was connected perfect monolithically. It was good validated to full scale of single pile Nailed-slab. The application of this curve on the full scale Nailed-slab with 1 row of piles will be discussed in this paper.

2. THEORITICAL BACKGROUND

2.1 Equivalent Modulus of Sub Grade Reaction

The analytical approach in determining equivalent modulus of sub grade reaction (k') is given as follows ([6], [14], [8]):

$$k' = k + \Delta k \tag{1}$$

Where k : modulus of sub grade reaction from plate load test (kN/m^3), Δk: additional modulus of subgrade reaction due to pile installing under slab (kN/m^3).

Considering the soil bearing pressure under an individual nailed-slab system, Hardiyatmo [6] proposed Eq. (2) in determining the additional modulus of sub grade reaction (Δk). The relative displacement between pile and soil is considered.

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

Where δ_0 : relative displacement between pile and soil (m), δ : deflection of surface of plate (m), A_s : surface area of pile shaft (m^2), s : width area of slab (m), a_d: adhesion factor (non-dimensional), c_u: undrained cohesion (kN/m^2), p_o': average effective over burden pressure along of pile (kN/m^2), K_d: coefficient of lateral earth pressure in pile surroundings (non-dimensional), ϕ_d: soil internal friction angle (degree).

The relation between δ_0/δ and slab deflection from pile model with a 4 cm diameter is also given by Hardiyatmo [6]. Hardiyatmo [22] re-published the relation between δ_0/δ and slab deflection for full scale model while the pile and slab was connected by bolt. The pile diameter was 20 cm dan the length of pile was varied between 1.0 m to 2.0 m. Puri [23] used invers of ratio of δ_s/δ_0 that is called displacement factor and presented in Figure1. Then, Eq.(2) can be re-written as follows

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

Where δ_a: tolerable deflection of rigid pavement slab (m). The curve of displacement factor is presented in Figure 1. Puri [24] also developed the curve of displacement factor for stiff clay based on Hardiyatmo [6].

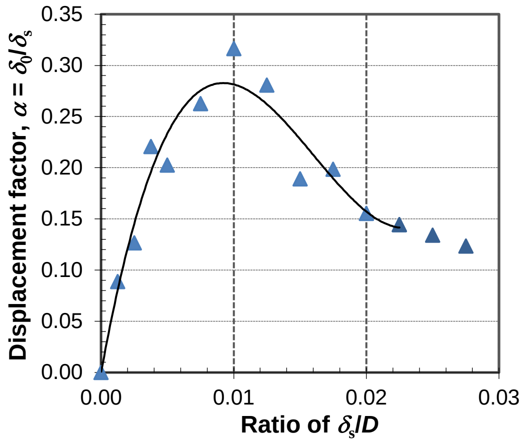


Figure 1 Correlation of displacement factor ($\alpha = \delta_0/\delta_s$) and ratio of δ_s/D for softclay [23]

For designing purposes, the relative displacement between pile and soil is difficult to define. Puri, et.al. [8] obtained Eq. (4) to define the additional modulus of sub grade reaction which considered the tolerable deflection of rigid pavement slab (δ_a). This approach is called Modified Hardiyatmo method.

$$\Delta k = \frac{0.4 f_s A_s}{\delta_a A_{ps}} \tag{4}$$

Where δ_a : tolerable deflection of rigid pavement slab (m), f_s: ultimate unit friction resistance of pile shaft (kN/m^2), A_s : surface area of pile shaft (m^2), A_{ps} : area of plate zone which supported by single pile (m^2).

Additional modulus of subgrade reaction for Nailed-slab in soft clay is expressed by

$$\Delta k = \frac{0.4 a_d c_u A_s}{\delta_a A_{ps}} \tag{5}$$

Where a_d: adhesion factor (non-dimensional), c_u: undrainedcohesion (kN/m^2).

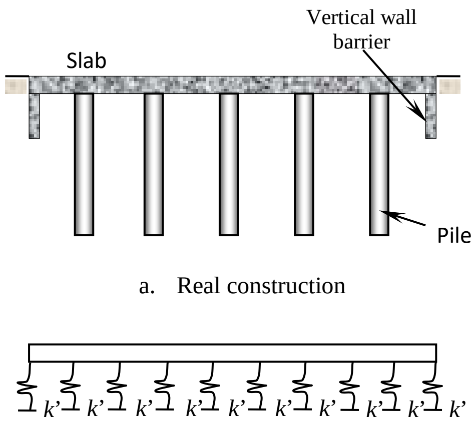
The modulus of sub grade reaction from the plate load test (k) is usually taken by using circular plate, and it should be corrected to slab shape of the nailed-slab.

2.2 Analysis of Deflection

Analysis of deflection of a nailed-slab by using equivalent modulus of subgrade reaction has been done by Hardiyatmo ([5], [6]), Puri, et.al. ([7], [8], [9], [10], [11]), Somantri [18] and Puri ([2], [23]). This modular was also implemented in cakar ayam analysis ([25], [26], [27]). In this paper the deflection will be analyzed by using Beam on

Elastic Foundation (BoEF) and finite element method (FEM). The theory of BoEF can be used to calculate the deflections due to the load acting on plate-supported piles ([5], [6], [15], [7], [8], [10], [20]). They used the Hetenyi's formulas. In this paper the Roark's formulas will be used. The deflection of the finite length of the beam resting on an elastic foundation due to a single concentrated load at any point is explained by using Roark's formulas in [28].

Figure 2 shows the approach model of Nailed-slab System for BoEF analysis. Figure 2a is represented the real construction and Figure 2b is represented the approach model. Vertical wall barriers on the both end of slab are neglected since BoEF cannot accommodate them. Piles are modelled by *k*' springs. In BoEF analysis, the k_0 value is changed by *k*' value which calculated by Eq.(1). Total deflection on the observed point is defined by superposition method of deflection caused by concentrated load and moment.



a. Real construction

b. Approach model

Figure 2 Approach model of Nailed-slab analysis in BoEF (vertical wall barriers are neglected) [2]

FEM analysis will use the commercial 2D Plaxis software. Nailed-slab will be analyzed by plain strain analysis. Pile will be transformed to continuous wall element by an equivalent thickness on plain strain geometry. Wall thickness will be calculated according to the ratio of pile section area to soil area which kept constant.

3. TESTING INVESTIGATION

This testing investigation was explained by Puri, et.al ([11], [29]) except for 1-pile row Nailed-slab and here is re-explained.

3.1 Soil Pond and Materials

Nailed-slab will be conducted on soft clay. A 6 m x 3.7 m soil pond was conducted by digging the existing soil until the depth of 2.5 m. On the 2 longer side was retained by masonry walls and supported by some temporarily girder. The anchorage system was built near the pond. Separator sheets were set on the pond walls and base to avoid the effects of surrounding existing soils. A 2.15 m of depth of test box was filled by soft clay which taken from District Ngawi, East Java, Indonesia. The soft clay properties are presented in [11] and [12]. There was soft cpay with plasticity index 59.98% and undrained shear strength 20.14 kN/m^2. The slab and piles were reinforced concrete. The concrete strength characteristic of slab and piles were 29.2 MPa and 17.4 MPa respectively.The flexural strength of the slab was 4,397.6 kPa. The coefficien of subgrade reaction based on standart plate load test was 15,000 kPa/m. This coefficien became 2,750 kPa/m after correction due to dimension and shape of nailed-slab (according to [30]).

3.2. Dimension of Nailed-slab

Test on 1 pile row Nailed-slab consisted of slab with 600 cm × 120 cm × 15 cm in dimension. Pile length was 150 cm and pile spacing was 120 cm. This model was obtained by cutting the 600 cm ×354 cm × 15 cm Nailed-slab became 3 parts where each part consisted of one pile row. The tested 1 pile row Nailed-slab was the middle one with slab dimension 600 cm × 120 cm × 15 cm as shown in Figure 3.

3.3. Testing Procedures

The steps in construction of Nailed-slab can be briefly described as follows: the pond was filled by soft clay until the soil thickness reach 2.15 m. Soft clay was spread about 15 cm in thickness per layer with controlled water content, and then it was compacted by 3 passing of manual compaction. Each soil layer thickness was decreased to about 10 cm per layer. Soft clay was cured by covering its surface with plastic sheet and wet carpet. 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 pre-drilled method and then continued by hydraulic jacking until the pile top reach the design level.

The pile was tested for compression bearing capacity and tension capacity. Soil was excavated for thickening slab. The 5 cm lean concrete then poured on the soil surface, and continued by conducting CBR test and plate load test after 3 days. The slab and vertical wall barrier reinforcement rebar were assembled. And then concrete was poured for slab. Slab was cured by wet carpet and after 28 days of concrete age the loading set up was assembled. Loading test was conducted on the slab for different load positions

(Point A and C in Figure 3a). Loads were transfer to the slab surface by using circular plate with 30 cm in diameter (the plate represents the single wheel load contact area). Then the instrumentations were recorded. Some photographs in construction and testing were presented in Figure 4.

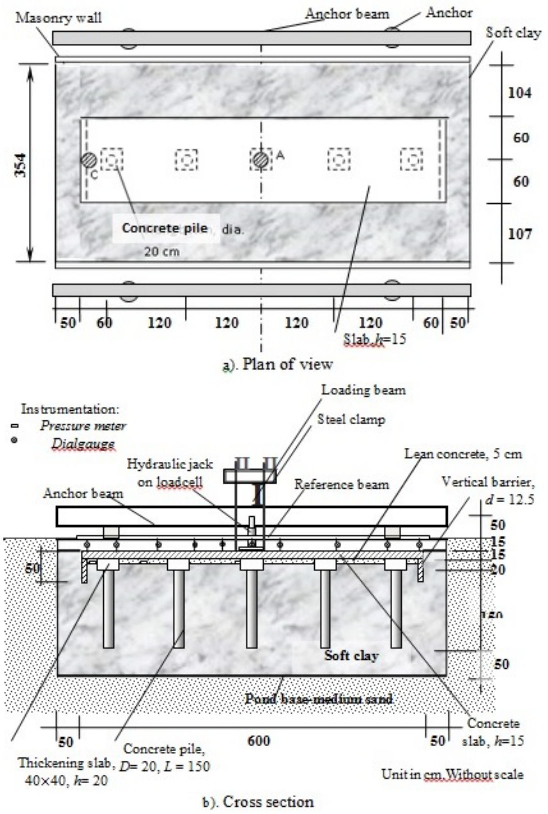


Figure 3 Schematic diagram of full scale Nailed-slab with 1 pile row [2]

3.4. Analysis Method

Numerical analysis will be conducted by using BoEF Analysis version 1.4 and 2D Plaxis v. 8.6.

Piles and soils were approached by vertical spring *k'* in BoEF analysis. In 2D Plaxis FEM (plain strain analysis), the soft clay was modeled by Mohr-Coulomb in un-drained condition. All structural elements were modeled by plate element in linear-elastic behavior. Lean concrete was modeled by soil with linear-elastic non-porous material. All structural elements were modeled by linear-elastic behavior. This 2D FEM used plain strain analysis type. Soil parameters and idealization of structural elements are presented in Table 1 and 2 respectively. The thickening slab was ignored since it could not be modeled by Plaxis 2D.

Figure 4 Photographs of loading tests on full scale Nailed-slab with 1 pile row (point C)

4. RESULTS AND DISCUSSIONS

4.1. The 2D Numerical Analysis of 1 Pile-row Nailed-slab

Result shows that the vertical wall barrier was not significant effect (Figure 5a). Deformed mesh is shown in Figure 6 which the end of slab was uplift.

Table 1 Model and parameters of soil

Parameters	Name/ Notation	Soft clay	Sand	Unit
Material model	Model	Mohr-Coulomb	Mohr-Coulomb	-
Material behavior	Type	*Undrained*	*Drained*	-
Saturated density	γ_{sat}	16.30	18.00	kN/m^3
Dry density	γ_d	10.90	20.00	kN/m^3
Young's Modulus	E	1,790.00	42,750.00	kPa
Poisson's ratio	ν	0.45	0.35	-
Undrained cohesion	c_u	20.00	1.00	kPa
Internal friction angle	ϕ	1.00	47.80	o
Dilatancy angle	ψ	0.00	2.00	o
Initial void ratio	e_0	1.19	0.50	-
Interface strength ratio	R	0.80	0.70	

Table 2 Model and parameters of structural elements in FEM 2D plain strain

Parameters	Name/ Notation	Lean concrete (LC)	Structural elements			Unit
			Slab	Vertical wall barrier	Pile	
Material model	Model	Volume element	*Plate*	*Plate*	*Plate*	-
Material behavior	Type	Elastic	Elastic	Elastic	Elastic	-
Normal stiffness	*EA*	-	4,554,000	3,795,000	616,696	kN/m
Flexural rigidity	*EI*	-	8,539	4.941	75,655	kNm^2/m
Equivalent thickness	*d*	-	0.15	0.125	0,027	m
Weight	*w*	-	3.60	3.00	29.12	kNm/m
Poisson's ratio	ν	0.2	0.15	0.15	0.20	-
Unit weight	γ	22	24	24	24	kN/m^3
Young's Modulus	*E*	17,900	25,300	25,300	19,600	MN/m^2
Interface strength ratio	*R*	0.80	0.80	0.80	0.80	-

It is quite different with result in full scale test. It is concluded that the Plaxis 2D could not model the vertical wall barrier which lower position than slab level, as well as could not model the thickening slab. The distribution of deflection along the slab will be discussed in section 4.2.

Lean concrete can reduce deflection and it significant under centric load (figure 5b). Reduced deflection tends to be higher by increasing the thickness of lean concrete.

4.2. Validation the Method of Preliminary Design Based on *k'*

The structure of pavement of full scale Nailed-slab System was calculated to find deflections and internal forces by using equivalent modulus of subgrade reaction (*k'*). The soil modulus of subgrade reaction for 1.20 m slab width was 3,300 kPa/m. Calculations were run by BoEF software. Design load was 40 kN single wheel load. Table 3 gives calculating results of *k'* where calculated by using Eq.(5) and Figure 1.

Calculated results based on Eq.(5) and Figure1 were good agreement with observation (Figure7). Calculated results based on Figure1 were higher than results based on Eq.(5) on the average 13.13%. It is caused by the equivalent modulus of subgrade reaction based on Figure1 higher than based on Eq.(5). Calculated deflections based on Eq.(5) and Figure1 were higher than observation on the average 51.37% and 66.20% respectively. These over-estimated results were caused of neglected to vertical wall barrier and thickening slab. BoEF distributes a concentrated load *P* over slab width, so the working load does not concentrated load in analyzing. It is also occurred to edge loads. The calculated deflections are linear-elastic and agreed with assumption of both methods. Results from 2D FEM were very close to observations (Figure 7). However, the distributions of deflections along the slab show that there are uplifts on the ends of slab (Figure 7b and 7d), but the soil were kept in contact with the slab (Figure 6a and 6b). It is supposedly that the software could not model the vertical wall barrier.

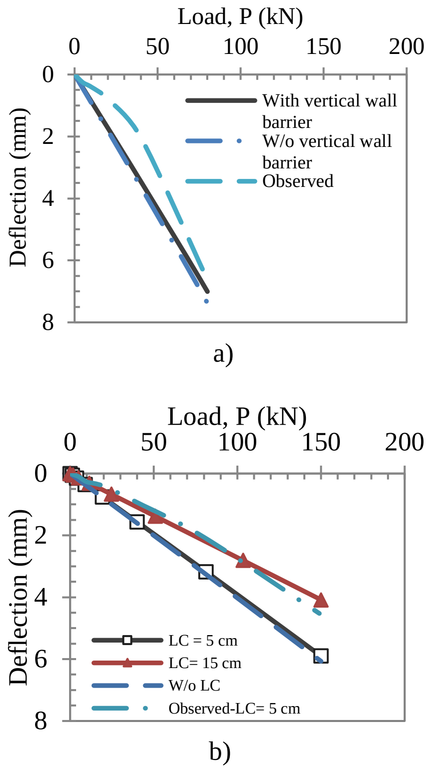
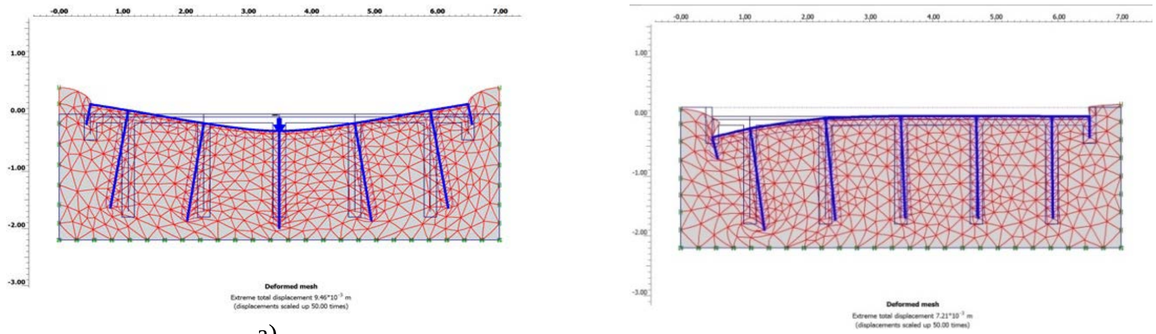


Figure 5 *P*-δ relationships from FEM 2D, a) Effect of vertical wall barrier for edge load on C, b) Effect of lean concrete for concentric load on A

Nailed-slab System under centric load of single wheel load (40 kN), maximum calculated deflection was 2.60 mm and it was not exceed the tolerable deflection (δ_a) = 5 mm.



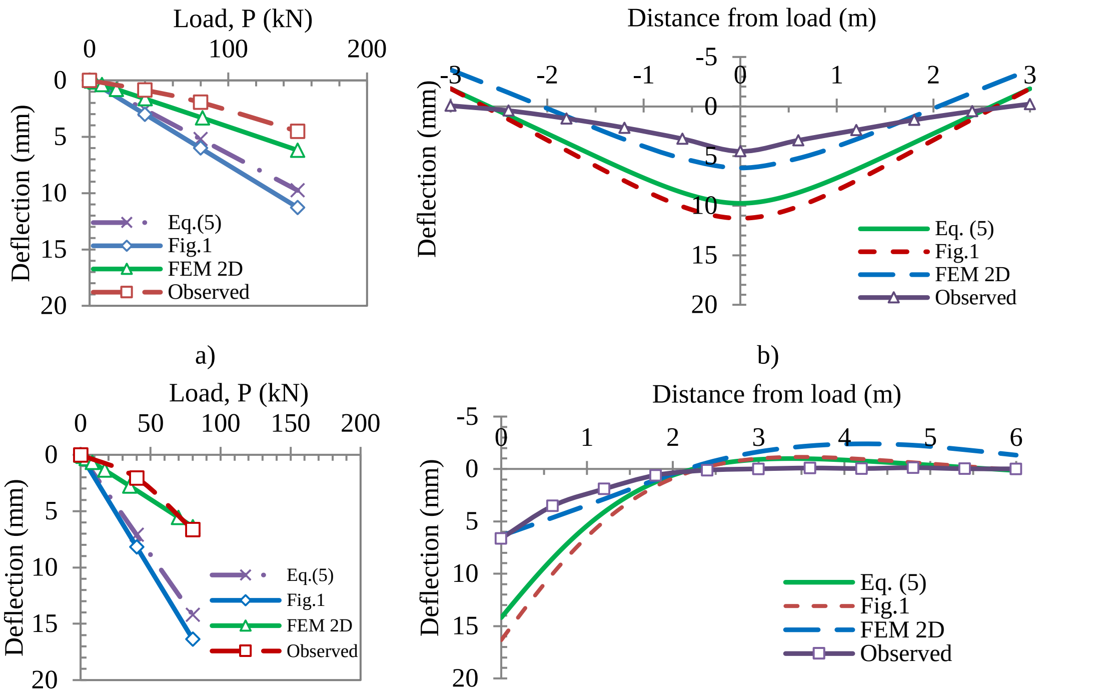
a) b)

Figure 6 Deformed mesh of 1-pile row Nailed-slab, a) for concentric load on A, b) for edge load on C

Table 3 Equivalent modulus of subgrade reaction for1 pile row number

Load position	Eq. (5)			Formula Hardiyatmo and Figure 1		
	k (kN/m^3)	Δk (kN/m^3)	k' (kN/m^3)	k (kN/m^3)	Δk (kN/m^3)	k' (kN/m^3)
Centric	3,300	1,175	4,755	3,300	380	3,680
Edge	3,300	1,175	6,710*	3,300	380	5,520*

Note: * k' for edge load was multiplied by multiplying factor 1.5



c) d)

Figure 7 Calculated deflections for full scale Nailed-slab with 1 pile row; a) P-δ concentric load, b) Deflection along slab-P_{max} concentric, c) P-δ edge load, d) Deflection along slab-P_{max} edge

Maximum calculated deflection due to edge load was 7.10 mm $>\delta_a$, but then the observed deflection for centric and edge load were only 1.21 mm and 2.04 mm respectively. Building on these facts, the design of Nailed-slab System is sufficiency. And by considering that in the field the Nailed-slab will be built in great quantities of piles, then the designing based on single pile row will result a design in safety zone. Therefore, the proposed formula and designing by considering single pile row were very sufficiency and will result a design in safety zone. And so do, it is easier in conducting the analysis.

4. CONCLUSION

According to loading test results on full scale Pavement of Nailed-slab with 1 pile row, analysis results, and discussion, several important conclusions can be concluded as follows

1. The tested model and full scale Nailed-slab system on soft clay showed the smooth deflected bowl. It indicates that the all piles abled to give similar responses. Compression and pull out capacity of piles were mobilized that made the slab keep contact with soil.
2. Based on observation, the system has higher stiffness to bear the loads. It was evidenced by linear elastic-response until load 80 kN. The higher stiffness of the system was experienced by small deflection about 2 mm due to centric load (P = 80 kN ≈ 2xsingle wheel load).
3. Installed piles under the slab which embedded into the soils were increase slab stiffness. It could be expressed by Δk. Such was the case that increasing in pile row number could increase the stiffness of the system which represented by k'.
4. Formula and curve of displacement factor for determining the additional modulus of subgrade reaction could be used for analyzing the Nailed-slab System. Both were validated by observation, BoEF analysis and 2D FEM. Analysis results were good agreement with observation, although tends less satisfy for edge loads. Employing k' in BoEF analysis was sufficiency enough. Into the bargain the proposed method of analysis was practical in use and timeless consuming. Designing the Nailed-slab by considering single pile row which used k' will result a safety design.

5. ACKNOWLEDGEMENTS

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Response by Authors to Reviewer's Remarks/Comments

Validating The Curve Of Displacement Factor Due To Full Scale Of One Pile Row Nailed-Slab Pavement System

Authors: Anas Puri, Hary C. Hardiyatmo, Bambang Suhendro, Ahmad Rifa'i

The authors have summarized their replies to the Reviewers' comments in this response letter in a two column format. A revised manuscript is submitted addressing all the comments to the Journal of GEOMATE for possible publication.

	Reviewer_A's Comments	*Authors Response*
1	This title needs to be improved; not standard to give such a title	The title is corrected as the reviewer's comments.
2	Improve this abstract; many English mistakes; not reading smoothly.	This abstract is corrected as per the reviewer's comments. The abstract and all entire paper was corrected by using Grammarly application.
3	Too many references which are not directly linked to the paper. Revise..	The references which are not directly linked to the paper were deleted as per the reviewer's comments.
4	Please check the title. Validation of the curve/ Validating the curve..	The title is revised as the reviewer's comments.
5	Many English mistakes.	The abstract and all entire paper was corrected by using Grammarly application.
6	Abstract - make sure it contains "background, methodology, results, and conclusions".	All abstract components are available as per the reviewer's comments.
7	Introduction - check whether it contains research significance?	Research significance is explained in the introduction as per the reviewer's comments.
8	The references cited in it are in order?	The references cited are in order as per the reviewer's comments.
9	Results - contains details explanation? Figures and table are correctly presented?	Results explanation, figures, and tables were correctly presented.
10	Conclusions - whether the key findings have been addressed and future work been outlined and recommended?	Key findings have been addressed and future work is added.
11	List of references – has the reference format followed the template?	List of references is formatted following the template.

The authors appreciate the valuable comments from the Reviewers.

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VALIDATING THE CURVE OF DISPLACEMENT FACTOR DUE TO FULL SCALE OF ONE PILE ROW NAILED-SLAB PAVEMENT SYSTEM

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ABSTRACT: A proposed alternative solution for rigid pavement problem on soft soil is the pavement of Nailed-slab System. It is a kind of developing the rigid pavement. Equivalent modulus of subgrade reaction (k') can be used to analyze Nailed-slab System. This modulus consists of the modulus of subgrade reaction from plate load test (k) and additional modulus of subgrade reaction due to pile installing (Δk). The Δk can also be determined by using the curve of the displacement factor. This research is aimed to validate the theory of additional modulus of subgrade reaction by using the curve of displacement factor due to the results of a prototype test of Nailed-slab with 1 pile row. The prototypes were constructed on soft clay and the connection between pile and slab was perfect monolithically. These systems were loaded by monotonic loads. Calculated deflections based on the method of the additional modulus of subgrade reaction were compared to the observed deflection and the results from the Finite Element Method. The result shows in good agreement with the observation. The proposed method of analysis was practical in use and timeless consuming. Designing the Nailed-slab by considering a single pile row which used k' will result in design in the safety zone.

Keywords: Nailed-slab system, soft clay, subgrade modulus, deflection, rigid pavement, displacement factor

1. INTRODUCTION

The pavement of Nailed-slab System was developed by changing the shell of the pavement of the chicken foot system (*Sistem Cakar Ayam*) with short piles in order to gain the efficiency of construction implementation [1]. The Nailed-slab System is not a kind of soil improvement although it is proposed to be applicable for soft soils [2]. This system is a kind of construction to increase the performance of rigid pavement on soft soils. This system consists of a thin pile cap that also serves as a rigid pavement, and short piles attached underneath. The composite system (consists of piles, slab, and soils surrounding the piles) is expected to be formed to bear the loads. The main function of the pile is as a nail to the slab so that the slab remains in contact with the subgrade. The installed piles under the slab also increase the slab stiffness [3]. Then the slab thickness can be decreased. The decreasing of slab thickness can reduce the weight of the structure and will be beneficial for soft soils [4]. Hence, a more durable pavement can be acquired with the result that the pumping could not take place and differential settlement could be reduced. Yet the consolidation problem of soft soils under the construction is not covered by the nailed-slab. This system recommended using thin pile cap (thickness about 12 cm to 25 cm) and short micro piles installed under the pavement slab. Micro piles have 12 cm – 20 cm in diameter, 1 m – 2 m length, and 1 m – 1.5 m pile spacing.

Hardiyatmo [1] conducted several studies on a nailed slab under dynamic loads, and studies on vertical loadings for soft clay were done by Hardiyatmo ([5], [6]), and Puri et al. ([3], [7], [8], [9], [10], [11], [12]), and for stiff lay by Nasibu [13], and Dewi [14]. Nailed-slab System due to tension loading was studied by Puri, et.al. [15] and Puri [16].

Design method by using an equivalent modulus of subgrade reaction (k') in Nailed-slab System analysis was proposed by Hardiyatmo [5]. This modulus consists of the modulus of subgrade reaction from plate load test (k) and additional modulus of subgrade reaction due to pile installing (Δk). Analysis method in determining the additional modulus of subgrade reaction was also proposed by Hardiyatmo [6]. And it was modified by Puri, et.al. [8] by considering the tolerable deflection or allowable deflection of pavement slab as an approach of safety construction and has good validation due to full-scale test [12].

Additional modulus of subgrade reaction considered displacement factor [6]. This factor is the ratio of the relative displacement between piles and soils (δ_0) and the pile head settlement (δ). The inverse of the displacement factor is the ratio of δ/δ_0. The curve of δ/δ_0 ratios was developed by Hardiyatmo [17] based on a full-scale test of single pile Nailed-slab in stiff clay. The pile and slab were connected by bolts. Puri [18] developed a curve of displacement factor ($\alpha=\delta_s/\delta_0$) based on a full-scale test on single pile Nailed-slab in soft clay. Pile and slab were connected perfectly monolithically. It was good validated to full scale of single pile Nailed-slab. The application of this curve on the full-scale Nailed-slab with 1 row of piles will be discussed in this paper.

2. THEORETICAL BACKGROUND

2.1 Equivalent Modulus of Sub Grade Reaction

The analytical approach in determining the equivalent modulus of subgrade reaction (k') is given as follows ([6], [14], [8]):

$$k' = k + \Delta k \tag{1}$$

Where k: modulus of subgrade reaction from plate load test (kN/m^3), Δk: additional modulus of subgrade reaction due to pile installing under the slab (kN/m^3).

Considering the soil bearing pressure under an individual nailed-slab system, Hardiyatmo [6] proposed Eq. (2) in determining the additional modulus of subgrade reaction (Δk). The relative displacement between pile and soil is considered.

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

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

The relation between δ_0/δ and slab deflection from pile model with a 4 cm diameter is also given by Hardiyatmo [6]. Hardiyatmo [17] re-published the relation between δ_0/δ and slab deflection for the full-scale model while the pile and slab were connected by a bolt system. The pile diameter was 20 cm dan the length of the pile was varied between 1.0 m to 2.0 m. Puri [18] used the inverse of the ratio of δ_s/δ_0 that is called displacement factor and presented in Figure1. Then, Eq.(2) can be re-written as follows

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

Where δ_a: tolerable deflection of rigid pavement slab (m). The curve of the displacement factor is presented in Figure 1. Puri [19] also developed the curve of displacement factor for stiff clay based on Hardiyatmo [6].

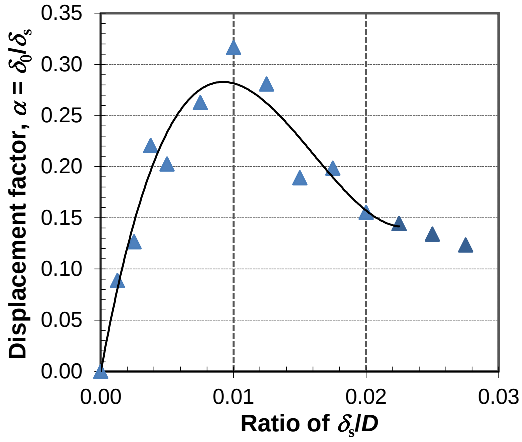


Fig.1 Correlation of displacement factor ($\alpha = \delta_0/\delta_s$) and the ratio of δ_s/D for soft clay [18]

For designing purposes, the relative displacement between pile and soil is difficult to define. Puri, et.al. [8] obtained Eq. (4) to define the additional modulus of subgrade reaction which considered the tolerable deflection of rigid pavement slab (δ_a). This approach is called Modified Hardiyatmo method.

$$\Delta k = \frac{0.4 f_s A_s}{\delta_a A_{ps}} \tag{4}$$

Where δ_a: tolerable deflection of rigid pavement slab (m), f_s: ultimate unit friction resistance of pile shaft (kN/m^2), A_s the surface area of pile shaft (m^2), A_{ps}: area of plate zone which supported by single pile (m^2).

Additional modulus of subgrade reaction for Nailed-slab in soft clay is expressed by

$$\Delta k = \frac{0.4 a_d c_u A_s}{\delta_a A_{ps}} \tag{5}$$

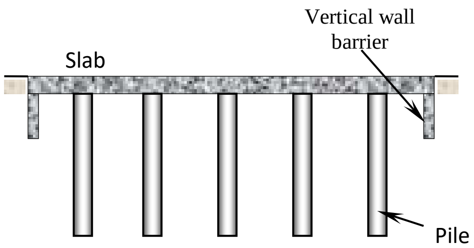
Where a_d: adhesion factor (non-dimensional), c_u: undrained cohesion (kN/m^2).

The modulus of subgrade reaction from the plate load test (k) is usually taken by using a circular plate, and it should be corrected to slab shape of the nailed-slab.

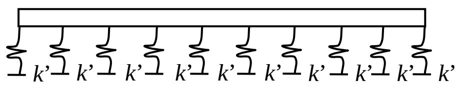
2.2 Analysis of Deflection

Analysis of deflection of a nailed-slab by using equivalent modulus of subgrade reaction has been done by Hardiyatmo ([5], [6]), Puri, et.al. ([7], [8], [9], [10], [11]) and Puri ([2], [23]). This modular was also implemented in Cakar Ayam analysis ([20], [21], [22]). In this paper, the deflection will be analyzed by using Beam on Elastic Foundation (BoEF) and finite element method (FEM). The theory of BoEF can be used to calculate the deflections due to the load acting on plate-supported piles ([5], [6], [15], [7], [8], [10], [15]). They used the Hetenyi's formulas. In this paper, the Roark's formulas will be used. The deflection of the finite length of the beam resting on an elastic foundation due to a single concentrated load at any point is explained by using Roark's formulas [23].

Figure 2 shows the approach model of Nailed-slab System for BoEF analysis. Figure 2a represents the real construction and Figure 2b represents the approach model. Vertical wall barriers on both ends of the slab are neglected since BoEF cannot accommodate them. Piles are modeled by k' springs. In the BoEF analysis, the k_0 value is changed by k' value which calculated by Eq.(1). Total deflection on the observed point is defined by the superposition method of deflection caused by concentrated load and moment.



a. Real construction



b. Approach model

Fig. 2 Approach model of Nailed-slab analysis in BoEF (vertical wall barriers are neglected) [2]

FEM analysis will use the commercial 2D Plaxis software. Nailed-slab will be analyzed by plain strain analysis. The pile will be transformed to continuous wall element by an equivalent thickness on plain strain geometry. Wall thickness will be calculated according to the ratio of pile section area to the soil area which kept constant.

3. TESTING INVESTIGATION

This testing investigation was explained by Puri, et.al ([11], [24]) except for 1-pile row Nailed-slab and here is re-explained.

3.1 Soil Pond and Materials

Nailed-slab will be conducted on soft clay. A 6 m x 3.7 m soil pond was conducted by digging the existing soil until the depth of 2.5 m. On the 2 longer sides was retained by masonry walls and supported by some temporary girder. The anchorage system was built near the pond. Separator sheets were set on the pond walls and base to avoid the effects of surrounding existing soils. A 2.15 m of the depth of test box was filled by soft clay which is taken from District Ngawi, East Java, Indonesia. The soft clay properties are presented in [11] and [12]. There was soft clay with plasticity index 59.98% and undrained shear strength 20.14 kN/m^2. The slab and piles were reinforced concrete. The concrete strength characteristic of slab and piles were 29.2 MPa and 17.4 MPa respectively. The flexural strength of the slab was 4,397.6 kPa. The coefficient of subgrade reaction based on standard plate load test was 15,000 kPa/m. This coefficient became 2,750 kPa/m after correction due to the dimension and shape of nailed-slab (according to [25]).

3.2 Dimension of Nailed-slab

Test on 1 pile row Nailed-slab consisted of the slab with 600 cm × 120 cm × 15 cm in dimension. Pile length was 150 cm and the pile spacing was 120 cm. This model was obtained by cutting the 600 cm × 354 cm × 15 cm Nailed-slab became 3 parts where each part consisted of one pile row. The tested 1 pile row Nailed-slab was the middle one with slab dimension 600 cm × 120 cm × 15 cm as shown in Figure 3. Test on 1 pile row Nailed-slab consisted of the slab with 600 cm × 120 cm × 15 cm in dimension. Pile length was 150 cm and the pile spacing was 120 cm. This model was obtained by cutting the 600 cm ×354 cm × 15 cm Nailed-slab became 3 parts where each part consisted of one pile row. The tested 1 pile row Nailed-slab was the middle one with slab dimension 600 cm × 120 cm × 15 cm as shown in Figure 3.

3.3 Testing Procedures

The steps in the construction of Nailed-slab can be briefly described as follows: the pond was filled by soft clay until the soil thickness reach 2.15 m. Soft clay was spread about 15 cm in thickness per layer with controlled water content, and then it was compacted by 3 passing of manual compaction. Each soil layer thickness was decreased to about 10 cm per layer. Soft clay was cured by covering its surface with plastic sheet and wet carpet. 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 by hydraulic jacking until the pile top reaches the design level.

The pile was tested for compression bearing capacity and tension capacity. The soil was excavated for thickening slab. The 5 cm lean concrete then poured on the soil surface and continued by conducting the CBR test and plate load test after 3 days. The slab and vertical wall barrier reinforcement rebar were assembled. And then concrete was poured for the slab. The slab was cured by wet carpet and after 28 days of concrete age, the loading set up was assembled. Loading test was conducted on the slab for different load positions (Point A and C in Figure 3a). Loads were transferred to the slab surface by using a circular plate with 30 cm in diameter (the plate represents the single wheel load contact area). Then the instrumentations were recorded. Some photographs in construction and testing were presented in Figure 4.

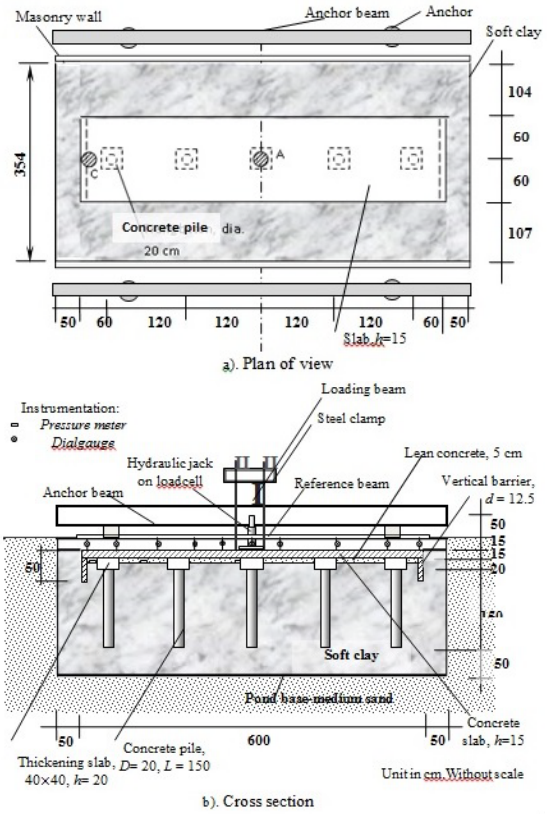


Fig.3 Schematic diagram of full-scale Nailed-slab with 1 pile row [2]

3.4 Analysis Method

The numerical analysis will be conducted by using BoEF Analysis version 1.4 and 2D Plaxis v. 8.6. Piles and soils were approached by vertical spring *k*' in BoEF analysis. In 2D Plaxis FEM (plain strain analysis), the soft clay was modeled by Mohr-Coulomb in un-drained condition. All structural elements were modeled by plate element in linear-elastic behavior. Lean concrete was modeled by soil with the linear-elastic non-porous material. All structural elements were modeled by linear-elastic behavior. This 2D FEM used plain strain analysis type. Soil parameters and idealization of structural elements are presented in Table 1 and 2 respectively. The thickening slab was ignored since it could not be modeled by Plaxis 2D.

Fig.4 Photographs of loading tests on full-scale Nailed-slab with 1 pile row (point C)

4. RESULTS AND DISCUSSIONS

4.1 The 2D Numerical Analysis of 1 Pile-row Nailed-slab

The result shows that the vertical wall barrier was not significant effect (Figure 5a). The deformed mesh is shown in Figure 6 which the end of the slab was uplift. It is quite different with the result in a full-scale test. It is concluded that the Plaxis 2D could not model the vertical wall barrier which lower position than slab level, as well as could not model the thickening slab. The distribution of deflection along the slab will be discussed in section 4.2.

Lean concrete can reduce deflection and it significant under centric load (Figure 5b). Reduced deflection tends to be higher by increasing the thickness of lean concrete.

4.2 Validation of the Method of Preliminary Design Based on *k*'

The structure of pavement of full-scale Nailed-slab System was calculated to find deflections and internal forces by using an equivalent modulus of subgrade reaction (*k*'). The soil modulus of subgrade reaction for 1.20 m slab width was 3,300 kPa/m. Calculations were run by BoEF software. Design load was 40 kN single wheel load. Table 3 gives calculating results of *k*' where calculated by using Eq.(5) and Figure 1.

Table 1 Model and parameters of soil

Parameters	Name/ Notation	Soft clay	Sand	Unit
Material model	Model	Mohr-Coulomb	Mohr-Coulomb	-
Material behavior	Type	*Undrained*	*Drained*	-
Saturated density	γ_{sat}	16.30	18.00	kN/m^3
Dry density	γ_d	10.90	20.00	kN/m^3
Young's Modulus	E	1,790.00	42,750.00	kPa
Poisson's ratio	v	0.45	0.35	-
Undrained cohesion	c_u	20.00	1.00	kPa
Internal friction angle	ϕ	1.00	47.80	^{o}
Dilatancy angle	ψ	0.00	2.00	^{o}
Initial void ratio	e_0	1.19	0.50	-
Interface strength ratio	R	0.80	0.70	

Table 2 Model and parameters of structural elements in FEM 2D plain strain

Parameters	Name/ Notation	Lean concrete (LC)	Structural elements			Unit
			Slab	Vertical wall barrier	Pile	
Material model	Model	Volume element	*Plate*	*Plate*	*Plate*	-
Material behavior	Type	Elastic	Elastic	Elastic	Elastic	-
Normal stiffness	*EA*	-	4,554,000	3,795,000	616,696	kN/m
Flexural rigidity	*EI*	-	8,539	4.941	75,655	kNm^2/m
Equivalent thickness	*d*	-	0.15	0.125	0,027	m
Weight	*w*	-	3.60	3.00	29.12	kNm/m
Poisson's ratio	v	0.2	0.15	0.15	0.20	-
Unit weight	γ	22	24	24	24	kN/m^3
Young's Modulus	*E*	17,900	25,300	25,300	19,600	MN/m^2
Interface strength ratio	*R*	0.80	0.80	0.80	0.80	-

Table 3 Equivalent modulus of subgrade reaction for1 pile row number

Load position	Eq. (5)			Formula Hardiyatmo and Figure 1		
	k (kN/m^3)	Δk (kN/m^3)	k' (kN/m^3)	k (kN/m^3)	Δk (kN/m^3)	k' (kN/m^3)
Centric	3,300	1,175	4,755	3,300	380	3,680
Edge	3,300	1,175	6,710*	3,300	380	5,520*

Calculated results based on Eq.(5) and Figure1 were good agreement with observation (Figure7). Calculated results based on Figure1 were higher than results based on Eq.(5) on the average 13.13%. It is caused by the equivalent modulus of subgrade reaction based on Figure1 higher than based on Eq.(5). Calculated deflections based on Eq.(5) and Figure1 were higher than an observation on the average 51.37% and 66.20% respectively. These over-estimated results were caused of neglected to vertical wall barrier and thickening slab. BoEF distributes a concentrated load *P* over slab width, so the working load does not concentrate load in analyzing. It also occurs to edge loads. The calculated deflections are linear-elastic and agreed with the assumption of both methods. Results from 2D FEM were very close to observations (Figure 7). However, the distributions of deflections along the slab show that there are uplifts on the ends of the slab (Figure 7b and 7d), but the soil was kept in contact with the slab (Figure 6a and 6b). It is supposed that the software could not model the vertical wall barrier.

Nailed-slab System under a centric load of single wheel load (40 kN), the maximum calculated deflection was 2.60 mm and it did not exceed the tolerable deflection (δ_a) = 5 mm.

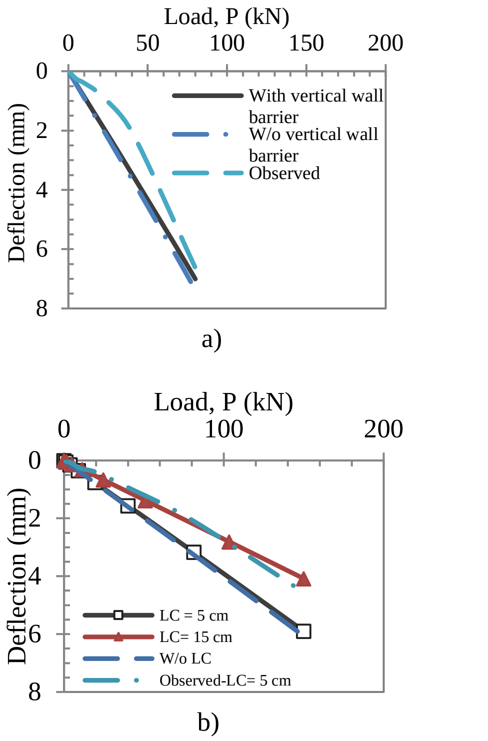


Fig.5 *P*-δ relationships from FEM 2D, a) Effect of vertical wall barrier for edge load on C, b) Effect of lean concrete for the concentric load on A

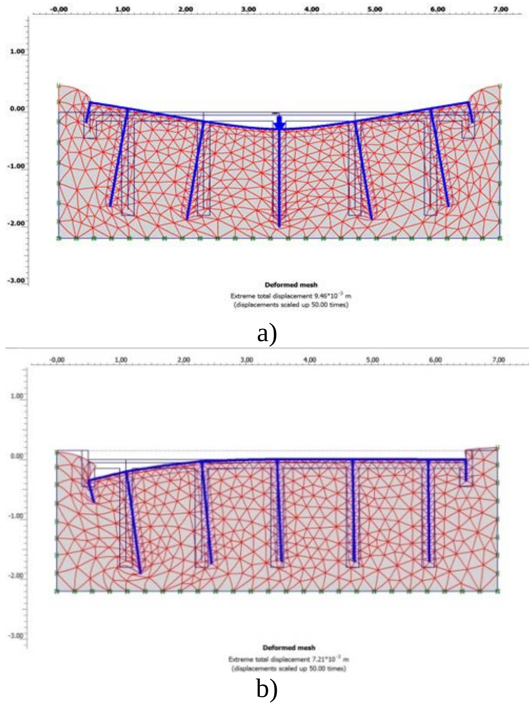


Fig.6 Deformed mesh of 1-pile row Nailed-slab, a) for concentric load on A, b) for edge load on C

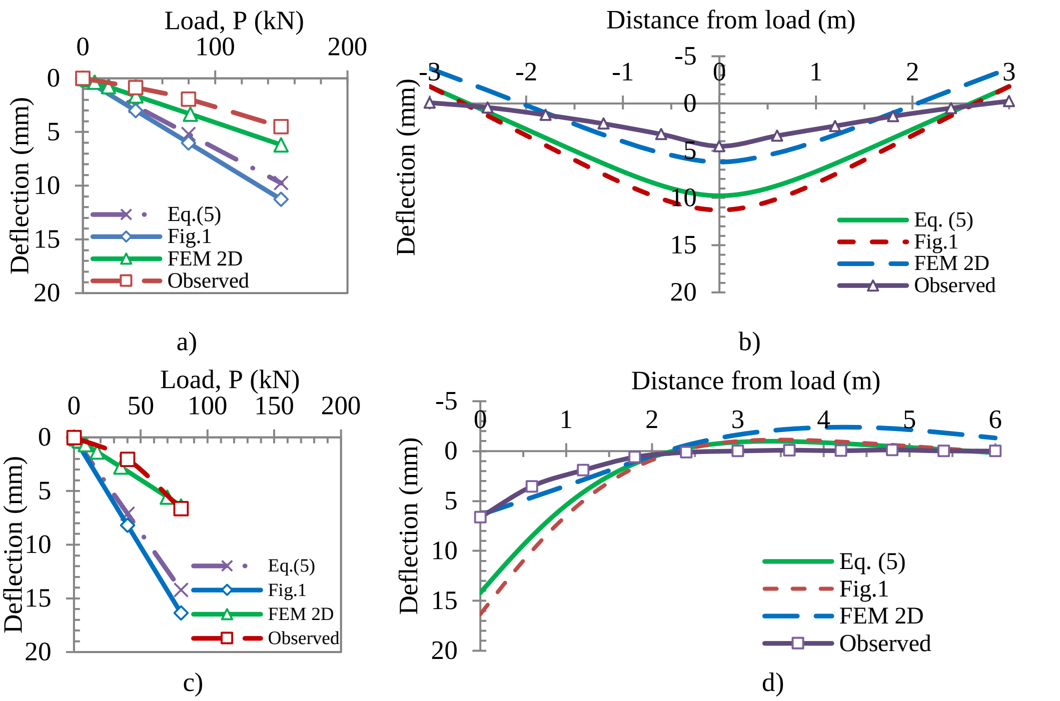


Fig.7 Calculated deflections for full scale Nailed-slab with 1 pile row; a) *P*-δ concentric load, b) Deflection along slab-P_{max} concentric, c) *P*-δ edge load, d) Deflection along slab-P_{max} edge

Maximum calculated deflection due to edge load was 7.10 mm > δ_a, but then the observed deflection for centric and edge load was only 1.21 mm and 2.04 mm respectively. Building on these facts, the design of Nailed-slab System is sufficiency. And by considering that in the field the Nailed-slab will be built in great quantities of piles, then the designing based on single pile row will result in a design in a safety zone. Therefore, the proposed formula and designing by considering single pile row were very sufficiency and will result in a design in a safety zone. And so do, it is easier in conducting the analysis.

5. CONCLUSIONS

According to loading test results on full-scale Pavement of Nailed-slab with 1 pile row, analysis results, and discussion, several important conclusions can be concluded as follows

1. The tested model and full-scale Nailed-slab system on soft clay showed the smooth deflected bowl. It indicates that all piles abled to give similar responses. Compression and pull out the capacity of piles were mobilized that made the slab keep contact with soil.
2. Based on observation, the system has a higher stiffness to bear the loads. It was evidenced by linear elastic-response until load 80 kN. The higher stiffness of the system was experienced by small deflection about 2 mm due to centric load (P = 80 kN ≈ 2xsingle wheel load).
3. Installed piles under the slab which embedded into the soils increased slab stiffness. It could be expressed by Δk. Such was the case that increasing in pile row number could increase the stiffness of the system which represented by k'.
4. Formula and curve of displacement factor for determining the additional modulus of subgrade reaction could be used for analyzing the Nailed-slab System. Both were validated by observation, BoEF analysis, and 2D FEM. Analysis results were good agreement with observation, although tends less satisfy for edge loads. Employing k' in BoEF analysis was sufficiency enough. Into the bargain, the proposed method of analysis was practical in use and timeless consuming. Designing the Nailed-slab by considering a single pile row which used k' will result in safety design.

Further research and developing the equivalent modulus of subgrade reaction for edge loads is necessary.

6. ACKNOWLEDGMENTS

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