International Journal of Civil & Environmental Engineering

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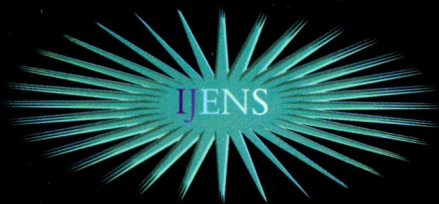
Determining Additional Modulus of Subgrade Reaction Based on Tolerable Settlement For The Nailed-slab System Resting on Soft Clay

Anas Puri, Hary Christady Hardiyatmo, Bambang Suhendro, and Ahmad Rifa'i

Abstract—**Nailed-slab System is a proposed alternative solution for rigid pavement problem on soft soils. Equivalent modulus of subgrade reaction (*k'*) can be used in designing of nailed-slab system. This modular is the cumulative of modulus of subgrade reaction from plate load test (*k*) and additional modulus of subgrade reaction due to pile installing (Δ*k*). A recent method has used reduction of pile resistance approach in determining Δ*k*. The relative displacement between pile and soils, and reduction of pile resistance has been identified. In fact, determining of reduction of pile resistance is difficult. This paper proposes an approach by considering tolerable settlement of rigid pavement. Validation is carried out with respect to a loading test of nailed-slab models. The models are presented as strip section of rigid pavement. The theory of beams on elastic foundation is used to calculate the slab deflection by using *k'*. Proposed approach can results in deflection prediction close to observed one. In practice, the Nailed-slab System would be constructed by multiple-row piles. Designing this system based on one-pile row analysis will give more safety design and will consume less time.**

Keywords—**soft clay, Nailed-slab System, friction pile, tolerable settlement, modulus of subgrade reaction.**

I. INTRODUCTION

THE Nailed-slab System first emerged from the idea of changing the shell of chicken foot foundation with short-friction piles in order to gain the efficiency of construction implementation [1]. This system was proposed as reinforcement of concrete rigid pavement on soft soil by using thin pile cap (thickness about 12 cm to 25 cm) which can reduce the weight of the structure and will be beneficial for soft soils [2]. Short micropiles were installed under the pave-

Anas Puri, S.T., M.T. Doctoral Candidate, Faculty of Engineering, Gadjah Mada University, Indonesia and Lecturer of Department of Civil Engineering Islamic University of Riau, Indonesia. Phone: +62 81 365 675 895, e-mail: anaspuri@yahoo.com

Hary Christady Hardiyatmo, Dr., Ir., M.Eng., DEA. Associate Professor Department of Civil and Environmental Engineering, Gadjah Mada University, Indonesia. e-mail: harychristady@yahoo.com

Bambang Suhendro, Ir., M.Sc., Ph.D. Professor Department of Civil and Environmental Engineering, Gadjah Mada University, Indonesia. e-mail: bbsuhendro@yahoo.com

Ahmad Rifa'i, Dr. es. sc. tech, Ir., M.T. Associate Professor Department of Civil and Environmental Engineering, Gadjah Mada University, Indonesia. e-mail: ahmad.rifai@tsipil.ugm.ac.id

ment slab. Micropiles have 12 cm – 20 cm in diameter, 1 m – 2 m length, and 1 m – 2 m pile spacing. Slab has double functions: as pavement structures and all at once as pile cap. Experimental modeling and analytical study have been done for soft soils ([2]; [1]; [3]; [4]; [5]; [6]; [7]; [8]; and [9]).

Deflection analysis of a nailed-slab by using equivalent modulus of subgrade reaction has been done by Hardiyatmo ([3], and [4]). This modular is the cumulative of modulus of subgrade reaction from plate load test (*k*) and additional modulus of subgrade reaction due to pile installing (Δ*k*). Reduction of pile resistance is one of aspects that need to be considered in determining Δ*k*. It is included in the relative displacement between the pile and soil. In fact, determining of the reduction of pile resistance for design purpose is difficult. Furthermore, this paper proposes an approach where pile friction resistance is fully mobilized and the tolerable settlement is considered. It is aimed at more ease in designing the Nailed-slab System.

II. ADDITIONAL MODULUS OF SUBGRADE REACTION (Δ*k*) BASED ON TOLERABLE SETTLEMENT

A. Modulus of Subgrade Reaction

The coefficient of subgrade reaction is one of the parameters that can be used in slab deflection analysis. The coefficient of vertical subgrade reaction (k_v) is defined by foundation pressure (*q*) divided by appropriate settlement (*δ*) of soil under foundation, and it is expressed by Equation (1). Multiplication of this coefficient by slab width gives the modulus of subgrade reaction.

$$k_v = \frac{q}{\delta} \qquad (1)$$

So, subgrade reaction is the distribution of soil reaction under raft foundation against the load of the foundation. Soil reaction is distributed non-linearly when foundation working load is uniform. For clay soil, the distribution of soil reaction has a convex shaped, which reaches maximum reaction near the edge of the foundation and is smallest at the center of the foundation.

In the nailed-slab system, the analytical approach in determining equivalent modulus of subgrade reaction (k') is given as follows ([4], [6], [9]):

$$k' = k + \Delta k \qquad (2)$$

Where

k : modulus of subgrade reaction from plate load test (kN/m³)

Δk : additional modulus of subgrade reaction due to pile installing (kN/m³)

Considering the single pile with an attached circular plate resting on soil, Hardiyatmo [4] proposed (3) in determining the Δk value.

$$\Delta k = \frac{\delta_0 A_s}{\delta^2 s^2}\left(a_d c_u + p_0 K_d \tan \varphi_d\right) \qquad (3)$$

Where

δ_0 : relative displacement between pile and soil (m)

δ : deflection of surface of plate (m)

A_s : surface area of pile shaft (m²)

s : pile spacing (m)

a_d : adhesion factor (non-dimensional)

c_u : undrained cohesion (kN/m²)

p_o' : average effective over burden pressure along of pile (kN/m²)

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 [4]. His results show that prediction of deflection tends to be over estimate (reached 35%) on the center loading, and under estimate (reached 14%) on edge loading. According to Puri et.al. [9], generally deflection prediction was slightly under estimate compared with observed deflection.

The derivation of the equation in determining additional modulus of subgrade reaction due to pile installing (Δk) by considering tolerable settlement approach is described in the next section.

B. Additional Modulus of Subgrade Reaction (Δk) based on Tolerable Settlement

Nailed-slab Resting on General Soils

The reaction under individual nailed-slab is shown in Fig. 1. The contribution by an end bearing pile (Q_b) can be ommitted according to the smallest dimension of the pile used in Nailed-slab System [4] or when the system resting on soft soils. So, the ultimate carrying capacity of the pile then becomes

$$Q_u = Q_s \qquad (4)$$

Where

Q_u : ultimate carrying capacity of pile (kN)

Q_s : ultimate shaft resistance of pile (kN)
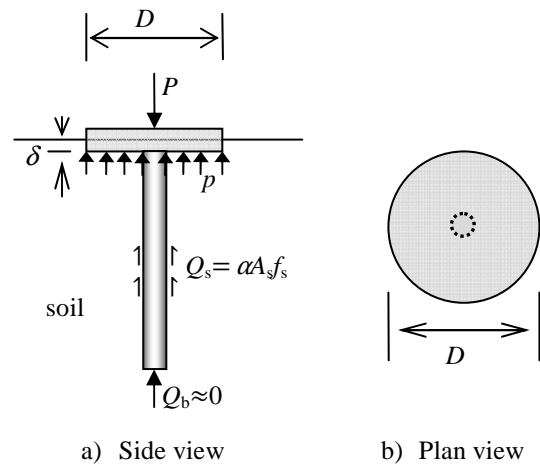

a) Side view   b) Plan view

Fig. 1. Soil bearing pressure under individual nailed-slab [4].

Ultimate shaft resistance of pile is expressed by

$$Q_s = A_s f_s \qquad (5)$$

Where

A_s : surface area of pile shaft (m²)

f_s : ultimate unit friction resistance of pile shaft (kN/m²)

Ultimate unit friction resistance of the pile shaft can be expressed by the classical equation:

$$f_s = a_d c_u + p_0' K_d tg\phi_d \qquad (6)$$

Where

a_d : adhesion factor (non-dimensional)

c_u : undrained cohesion (kN/m²)

p_o' : average effective over burden pressure along of pile (kN/m²)

K_d : coefficient of lateral earth pressure in pile surroundings (non-dimensional)

ϕ_d : soil internal friction angle (degree)

Displacement on the loading plate differs due to the relative displacement between the soil and the pile (δ_0). Since soils under the loaded plate is moved together with pile moving down, the relative displacement between the soil and the pile is always smaller than the displacement on the loading plate surface (δ_s). So, the ultimate unit friction resistance of the pile shaft has not been fully mobilised yet [4]. The displacement factor [4] or namely the reduction factor for pile resistance (α) should be considered. Therefore

$$Q_s = \alpha A_s f_s \qquad (7)$$

The mobilised unit pile shaft resistance can be expressed as [4]

$$R_s = \alpha f_s \qquad (8)$$

The pile friction modulus is defined as [4]

$$k_t = \frac{R_s}{\delta_p} \qquad (9)$$

Equation (9) can be expressed as

$$k_t = \beta R_s \qquad (10)$$

Where

R_s : mobilized unit friction on the pile shaft (kN/m^2)
k_t : pile friction modulus (kN/m^3)
β : factor of pile unit resistance (m^{-1}), defined as $\beta = 1/\delta_p$
δ_p : displacement of pile head (m)

The additional subgrade modulus under the plate due to pile installation is expressed as the contribution of pile resistance. It can be determined using the equation

$$\Delta k\, A_{ps} = k_t\, A_s \qquad (11)$$

Where

A_{ps} : area of plate zone which supported by single pile (m^2)
$A_{ps} = s^2$ according to [4] for nailed-slab
s : pile spacing (m)
A_s : surface area of pile shaft (m^2)

Substituting (10) into (11), we have

$$\Delta k = \frac{\beta R_s A_s}{A_{ps}} \qquad (12)$$

Subtituting (8) into (12), we obtain

$$\Delta k = \frac{\beta \alpha f_s A_s}{A_{ps}} \qquad (13)$$

For designing necessity, it is difficult to determine the reduction factor of pile resistance (α). According to [4], this factor is defined as

$$\alpha = \delta_0/\delta_s \qquad (14)$$

The mobilised unit pile shaft resistance is still in the elastic zone. According to the rule of thumb in determining the allowable pile bearing capacity which is usually taken at 1/2.5 of ultimate capacity, furthermore, the reduction factor of pile resistance is approached by 1/2.5. Another point that should be considered is tolerable settlement of rigid pavement slab (δ_a). Damages of rigid pavement slab are usually caused by differential settlement rather than total settlement. For rigid pavements, the general guide is that D/T^2 should be less than 2.5E-4/m where D is the depth of differential settlement and T is the half wave length of settlement [10]. Allowable strain in concrete can also be considered to tolerate the maximum differential settlement of the slab. The simple relation ($\varepsilon = t/R$) can be used to assess the maximum strain in a pavement due to curvature where t = thickness of pavement and R = radius of curvature [10].

By taken $\alpha = 1/2.5$ and assuming the displacement of pile head equals to the tolerable settlement of rigid pavement slab ($\delta_p = \delta_a$; then $\beta = 1/\delta_a$), therefore, (13) can be written as

$$\Delta k = \frac{f_s A_s}{2.5 \delta_a A_{ps}} = \frac{0.4 f_s A_s}{\delta_a A_{ps}} \qquad (15)$$

Furthermore, (2) can be written as

$$k' = k + \frac{0.4 f_s A_s}{\delta_a A_{ps}} \qquad (16)$$

The value of $\alpha = 1/2.5 = 0.4$ is very close to δ_0/δ_s from [4] for δ_s more than 2.5 mm, according to the model test.

By substituting (5) into (15) and (16), we can also obtain (17) and (18) respectively

$$\Delta k = \frac{0.4 Q_s}{\delta_a A_{ps}} \qquad (17)$$

$$k' = k + \frac{0.4 Q_s}{\delta_a A_{ps}} \qquad (18)$$

The modulus of subgrade 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. Equation (16) or (18) would be a practical approach for determining the equivalent modulus of subgrade reaction in designing the Nailed-slab System.

Nailed-slab Resting on Soft Soils

End bearing resistance is ignored for nailed-slabs on soft soils. Ultimate unit friction resistance of the pile shaft in saturated clay is expressed by

$$f_s = a_d c_u \qquad (19)$$

Where

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

Substituting (19) into (15)

$$\Delta k = \frac{0.4 a_d c_u A_s}{\delta_a A_{ps}} \qquad (20)$$

Substituting (20) into (2), we obtain

$$k' = k + \frac{0.4 a_d c_u A_s}{\delta_a A_{ps}} \qquad (21)$$

For c-ϕ soil, ultimate unit friction resistance of the pile shaft is expressed by (6).

III. ANALYSIS OF DEFLECTION

An attempt was made to calculate the deflections due to the load acting on flexible plate-supported piles by applying the theory of beams on elastic foundation ([3]; [4]; [7]; [9]). For finite length of the beam resting on an elastic foundation due to a single concentrated load at any point, the deflection can be defined as [11]

$$\delta = \frac{P\lambda}{k}\frac{1}{\sinh^2 \lambda l - \sin^2 \lambda l}\{2\cosh \lambda x \cos \lambda x$$

$$(\sinh \lambda l \cos \lambda a \cosh \lambda b - \sin \lambda l \cosh \lambda a$$

$$\cos \lambda b + (\cosh \lambda x \sin \lambda x + \sinh \lambda x \cos \lambda x) \qquad (22)$$

$$[\sinh \lambda l (\sin \lambda a \cosh \lambda b - \cos \lambda a \sinh \lambda b) +$$

$$\sin \lambda l (\sinh \lambda a \cos \lambda b - \cosh \lambda a \sin \lambda b)]\}$$

Where

P : concentrated load acting on beam (kN)

λ : flexibility of beam; $\lambda = \sqrt[4]{\dfrac{k}{4EI}}$

k : modulus of subgrade reaction (kN/m^2/m);
$k = k_v B$.
B : width of beam (m)
E : modulus of elasticity of beam (kN/m^2)
I : moment of inertia (m^4)
a and b : distance distinct by Fig. 2.

The k is replaced by k' for analysis of nailed-slab system. Equation (22) is used as given when x is less than the distance a, and x is measured from C. When x is larger than a, a is replaced by b, and x is measured from D.
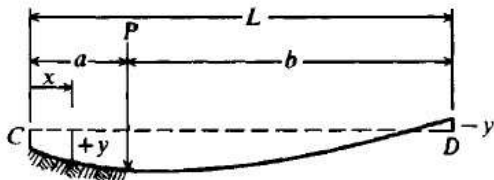

Fig. 2. Beam on elastic foundation with finite length [12].

IV. TESTING INVESTIGATION

The proposed approach will be validated by using data from Puri, et.al. [9] for a nailed-slab without a vertical barrier. The loading test set up is shown in Fig. 3 and models of concrete slabs supported by piles and the photograph of the testing are shown in Fig. 4 and 5 respectively. All models are presented as strip section of the rigid pavement. Soft clay parameters are given in Table 1. Slabs and piles are made by reinforced concrete. Slab reinforcement was wire mesh with 3 mm-wire diameters, and 5 cm × 5 cm meshing. Pile models were reinforced by 3mm-aluminium wire diameter. Model scale for geometry was 1 : 5. Piles and slabs were connected monolithically. Nailed-slab models consist of
a). nailed-slab with one row of piles (consist of 6 piles); 120 cm × 20 cm × 3 cm slab, 20 cm pile spacing ($s/d = 5$), pile diameter $d = 4$ cm, pile length $L = 40$ cm (Fig. 3a).

b). nailed-slab with two rows of piles (consist of 12 piles); 120 cm × 40 cm × 3 cm slab, 20 cm pile spacing ($s/d = 5$), pile diameter $d = 4$ cm, pile length $L = 40$ cm (Fig. 3b). This model was conducted to study the effect of row of pile due to the equivalent modulus of subgrade reaction.

The slabs and piles have the modulus of elasticity $E_c = 17,000$ MPa. Soft clay has a 15,000 kPa/m modulus of subgrade reaction from plate load test with 30 cm in plate diameter. Lean concrete has a 71,100 kPa/m modulus of subgrade reaction from plate load test with 20 cm in plate diameter. These moduli of subgrade reaction was corrected due to the shape of the slab according to [13], and resulted in 16,250 kPa/m and 51,350 kPa/m for soft clay and lean concrete respectively. For homogenous soft clay, correction due to depth of the foundation is not required.
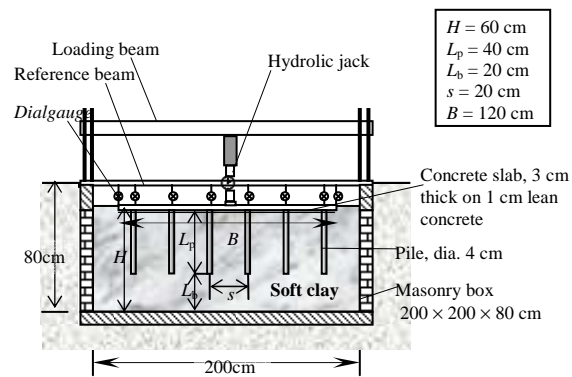

Fig. 3. Schematic set-up of loading test on concrete slab supported by piles [8].
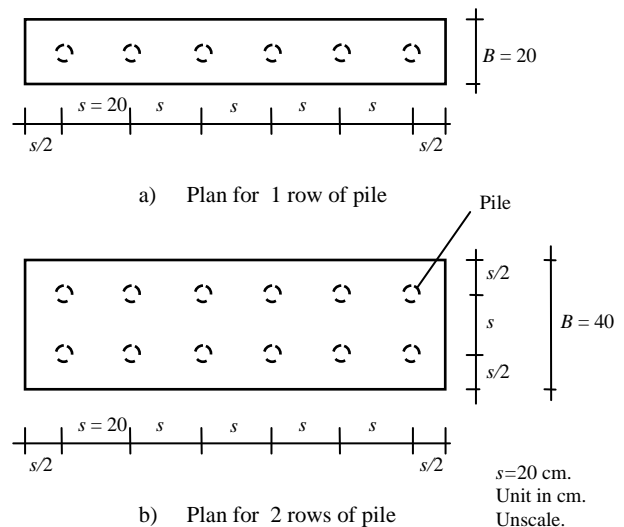

Fig. 4. Plan view of model types.

The steps of testing consist of soil preparation, plate load test on the soil, soil sampling for soil properties test, lean concrete pouring, plate load test for one week age of lean concrete, pile installation by hydraulic jack, slab reinforcement and pouring concrete slab. Then, the surface of the soft soil is covered by plastic sheets and wet cloths which

are sprayed by water twice a day. Loading on the slab is conducted after the slab reaches 28 days of age. Concentrated loadings are applied at the center and edge of slab. The reading of deflection dial gauge is noted when the rate of increase in deflection is less than 0.03 mm/min (or 0.01 in./min).
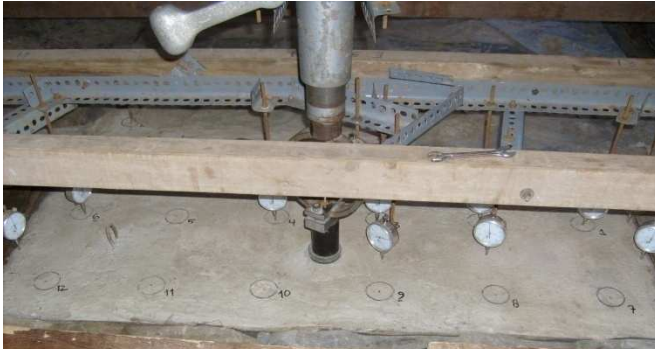
bears the load.

Fig. 6. Distribution of deflection along slab of nailed-slab system for one row of pile with center loading.

Fig. 5. Photograph of center loading test on nailed-slab with two rows of piles.

Fig. 7. Distribution of deflection along slab of nailed-slab system for one row of pile with edge loading.

TABLE 1
SOFT CLAY PROPERTIES [9]

No.	Parameters	Unit	Value
1	Specific gravity, G_s	-	2.3
2	Atterberg's limits:		
	- Liquid limit, LL	%	68.39
	- Plastic limit, PL	%	29.55
	- Shrinkage limit, SL	%	7.68
	- Plasticity index, PI	%	38.84
3	Moisture content, w	%	42.4
4	Percentage of fine grains	%	93.85
5	Saturated density, γ_{sat}	kN/m^3	17.0
6	Undrained cohesion, c_u	kN/m^2	21
7	Soil classification: USCS	-	CH
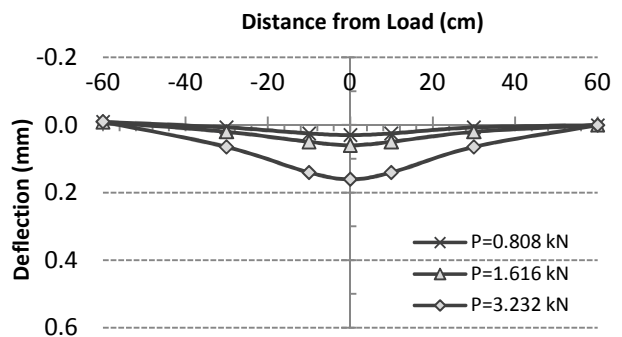
Fig. 8. Distribution of deflection along slab of nailed-slab system for two rows of pile with center loading.

V. RESULTS AND DISCUSSION

A. *Loading Test Results*

Distribution of deflection along the slab of a nailed-slab system for one row of piles is shown in Fig. 6 and 7 for center loading and edge loading respectively. And distribution of deflection along the slab for two rows of piles is shown in Fig. 8 and 9 for center loading and edge loading respectively. It is concluded that the maximum deflection of the slab for edge loading is 4 times the maximum deflection of center loading. Generally, there is no significant uplift of the slab end. The capability of the nailed-slab system is higher due to center loading than edge loading. The two-pile row of nailed-slab system has lower deflection than one row-pile system. It is caused by increase in stiffness of system due to pile installation under the slab and the increase of slab area which

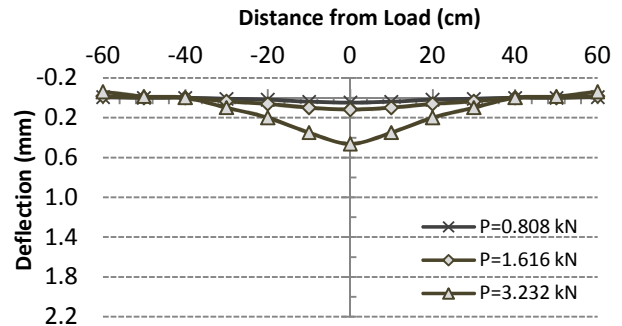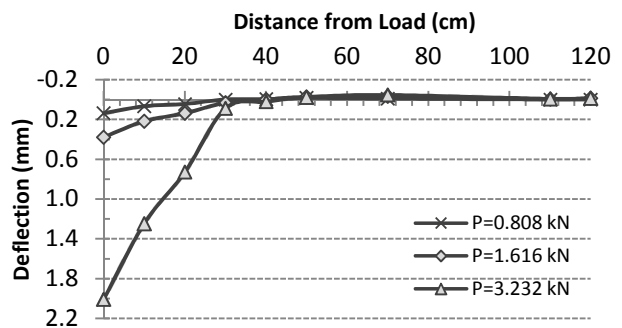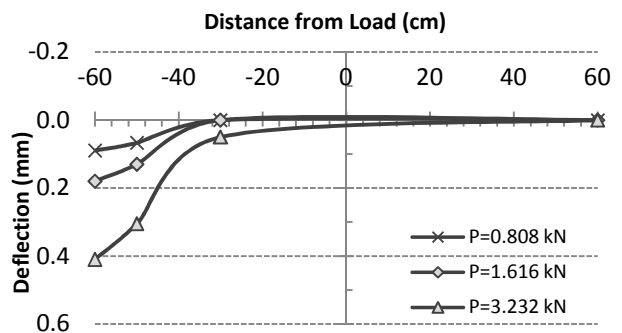Fig. 9. Distribution of deflection along slab of nailed-slab system for two rows of pile with edge loading.

B. Additional Modulus of Subgrade Reaction

Additional modulus of subgrade reaction due to one row pile installation is calculated by (19), (15) and (16), and results are shown in Table 2. The tolerable settlements (δ_a) were taken as observed maximum deflections. Modulus subgrade reaction for lean concrete is 51,350 kPa/m. Equivalent modulus of subgrade reactions are included in Table 2. It is shown that k' and Δk are lower for edge loading.

The k' values in Table 2 are used to calculate nailed-slab deflection. Calculation results are shown in Fig. 10 and 11 for center loading and edge loading respectively. Good results are obtained in the sense that the calculated settlement is in good agreement with observation. P-δ graph is shown in Fig. 12 for all type of loadings. Calculated settlement tends to be in good agreement with observed settlement, although for edge loading it tends to be over-estimated (Fig. 12). Similar results are also found by [4] and [9].

TABLE 2
EQUIVALENT MODULUS OF SUBGRADE REACTION FOR ONE-ROW PILE SYSTEM

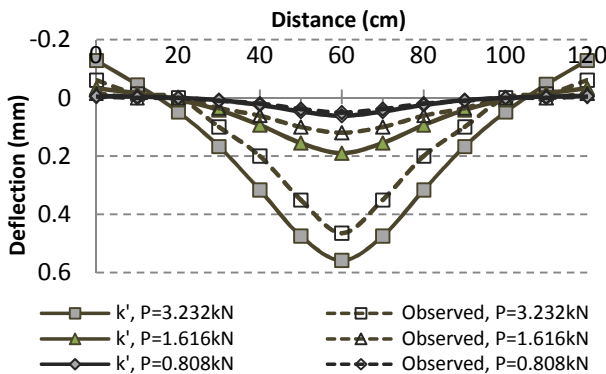| No.	Loading Type	Loads, P (kN)	Observed δ_a (mm)	Δk (kPa/m)	k' (kPa/m)
1	Center	3.232	0.47	17,060	68,410
		1.616	0.12	60,455	111,805
		0.808	0.05	145,093	196,443
2	Edge	3.232	2.01	3,989	55,339
		1.616	0.38	19,091	70,441
		0.808	0.14	51,819	103,169

Fig. 10. Distribution of deflection of one-row pile nailed-slab for center loadings.

C. Effects of Lean Concrete (LC)

The maximum deflection observed is used as tolerable settlement in the determining $\Delta k'$. Two kind of analysis was considered as follows:

1. Nailed-slab with lean concrete (LC). The k' is calculated on Table 2. Value of k' is based on subgrade reaction modulus of lean concrete.

2. Nailed-slabs without considering lean concrete. Value of k' which is based on soft clay subgrade reaction modulus is given in Table 3.
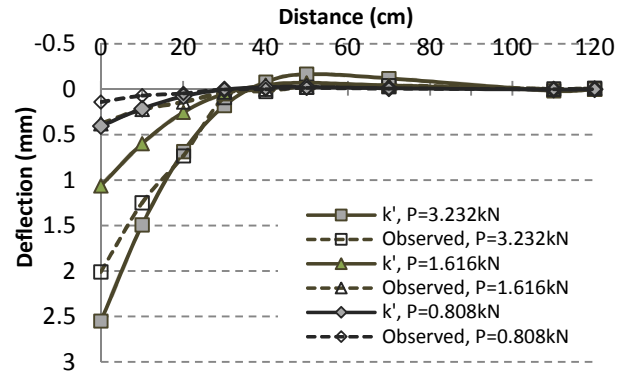

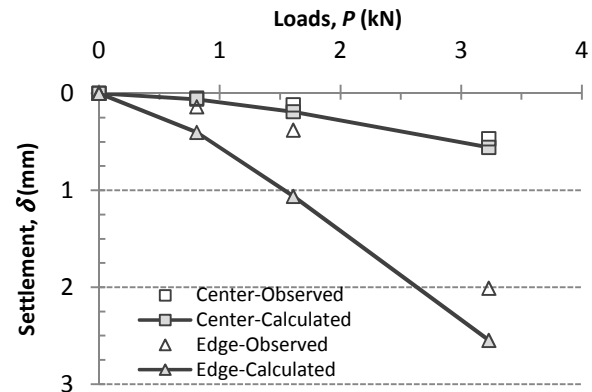Fig. 11. Distribution of deflection of one-row pile nailed-slab for edge loadings.

Fig. 12. P-δ relationship on loading point between calculation and observation of one-row pile nailed-slab.

TABLE 3
EQUIVALENT MODULUS OF SUBGRADE REACTION BASED ON k OF SOIL (LOAD P = 3.232 kN)

Loading Types	k (kPa/m)	Observed δ_a (mm)	Δk (kPa/m)	k' (kPa/m)
Center	16,250	0.47	17,060	33,310
Edge	16,250	2.01	3,989	20,239

Analysis and observation of the deflection distribution along the slab are shown in Fig. 13 for center loading and Fig. 14 for edge loading. It appears that analytical of nailed-slabs with lean concrete results in good agreement with observed deflection. Otherwise, nailed-slab without considering lean concrete tends to be overestimate 112% and 170% for center load and edge load respectively. This indicates that the count of deflection of the Nailed-slab System on the basis of soil modulus of subgrade reaction (regardless of k of lean concrete) has more safety. The contribution of lean concrete stiffness is neglected in design, and then implemented in practice.
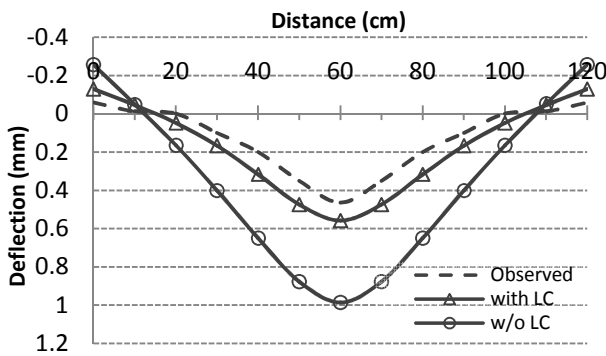
Fig. 13. Deflection distribution along slab for center loading Q = 3.23 kN considering nailed-slab with/without LC.
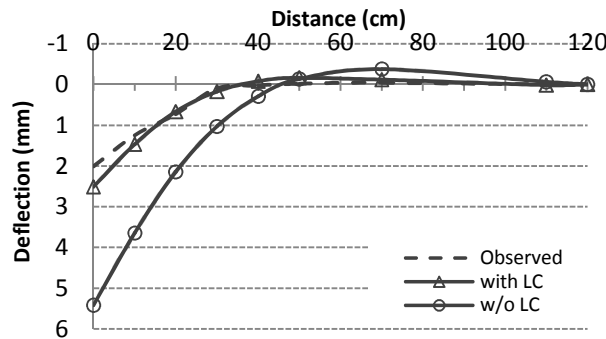

Fig. 14. Deflection distribution along slab for edge loading Q = 3.23 kN considering nailed-slab with/without LC.

D. Effects of Number of Pile Rows

Two kinds of calculations are conducted as follows,

1. The maximum deflection observed from two-rows nailed-slab is used as tolerable settlement in the determining $\Delta k'$. Table 4 shows equivalent modulus of subgrade reaction based on observed deflection.

2. By using defined tolerable settlement. The equivalent modulus of subgrade reaction based on defined tolerable settlement is shown in Table 5. Tolerable settlement is 0.5 mm for center load and 2.0 mm for edge load. All tolerable settlements are used for all loading works.

TABLE 4
EQUIVALENT MODULUS OF SUBGRADE REACTION
FOR 2-PILE ROW OF NAILED-SLAB SYSTEM
BASED ON OBSERVED DEFLECTION

No.	Loading Type	Loads, P (kN)	Observed δ_a (mm)	Δk (kPa/m)	k' (kPa/m)
1	Center	6.464	0.38	21,101	46,776
		3.232	0.16	50,114	75,789
		1.616	0.06	133,638	159,313
2	Edge	3.232	0.41	19,557	45,232
		1.616	0.18	44,546	70,221

Additional modulus of subgrade reaction is considered not changed even though the number of rows of piles is increased.

It is based therefore on no change in the pile length and the pile spacing. Therefore, the change of equivalent modulus of subgrade reaction (k') is due to changes in the modulus of subgrade reaction of the lean concrete (k). The lean concrete subgrade reaction modulus is changed as a result of changes in the width of the slab, where the width of the slab for 2 rows of piles is 40 cm. After correction to the width of the slab in two-row pile nailed-slab, the k' for lean concrete becomes 25,675 kPa/m.

TABLE 5
EQUIVALENT MODULUS OF SUBGRADE REACTION
FOR 2-PILE ROW OF NAILED-SLAB SYSTEM
BASED ON DEFINED TOLERABLE SETTLEMENT

No.	Loading Types	k (kPa/m)	Defined δ_a (mm)	Δk (kPa/m)	k' (kPa/m)
1	Sentris	25,675	0.5	16,037	41,712
2	Pinggir	25,675	2	4,009	29,684

Analysis results based on observed settlement and observation of the deflection distribution along the slab are shown in Fig. 15 for centric load and Fig. 16 for the edge loading. It appears that all analytical results over estimate the entire loading. This indicates that the analysis of deflection of the Nailed-slab System on the basis of a one pile row to be safer when applied to Nailed-slab System consisting of more than one pile row. It is caused by pile group resistance higher and increase in slab stiffness according to piles installation ([8], [9]).
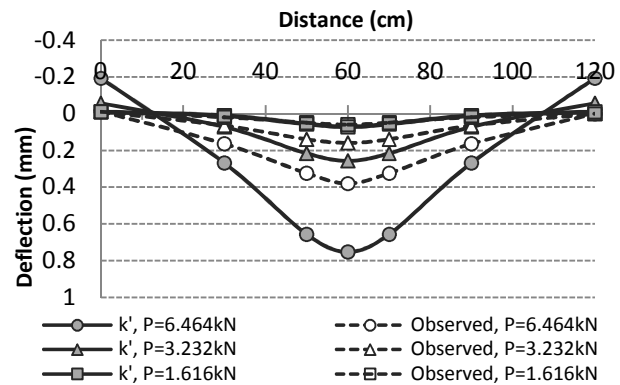

Fig. 15. Deflection distribution along slab for center loading of two-pile row nailed-slab system. Δk based on observed deflection.

Fig. 17 to 19 show the results of analysis of deflection where Δk based on defined tolerable settlement. Fig. 17 to 19 are intended for different load types and intensities. All deflection results are shown very over-estimated and more over-estimated than Δk based on observed deflection. It is proved again that the analysis of deflection of the Nailed-slab System on the basis of a one-pile row is safer when applied to Nailed-slab System consisting of more than one pile row. Using defined tolerable settlements tend to put the design in safer zone.
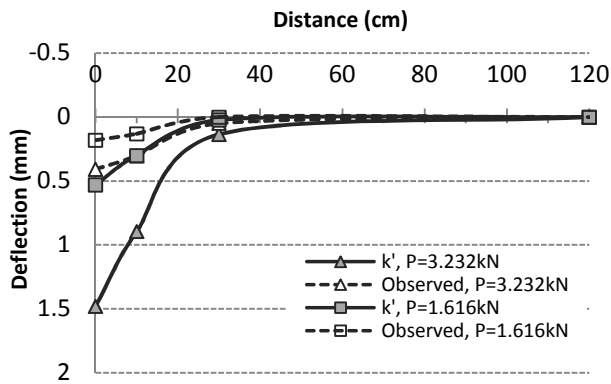
Fig. 16. Deflection distribution along slab for edge loading of two-pile row nailed-slab system. Δk based on observed deflection.
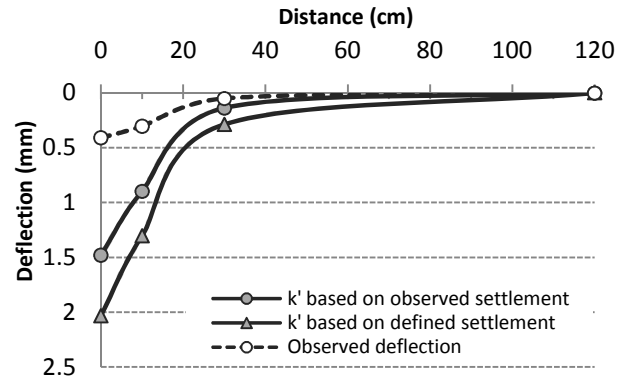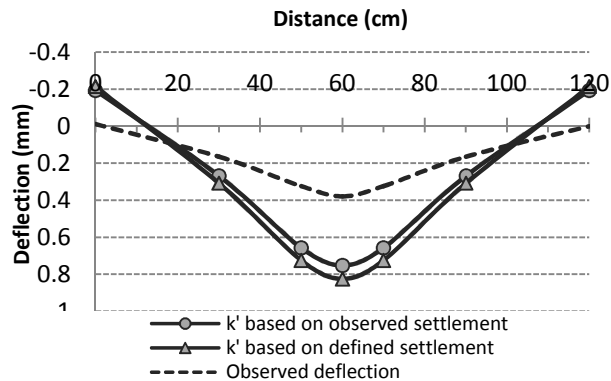

Fig. 17. Deflection distribution along slab for center loading (P=6.646 kN) of two-pile row nailed-slab system. Δk based on defined tolerable settlement.

Fig. 18. Deflection distribution along slab for center loading (P=3.323 kN) of two-pile row nailed-slab system. Δk based on defined tolerable settlement.
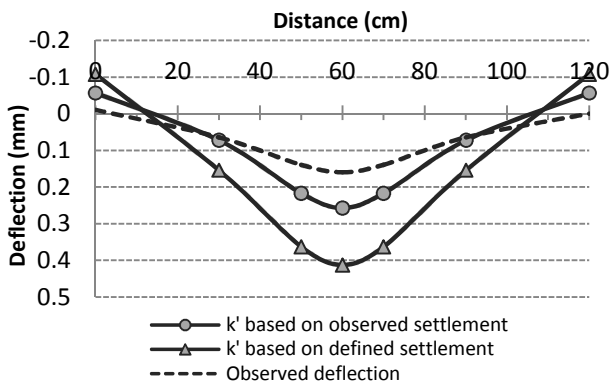

Fig. 19. Deflection distribution along slab for edge loading (P=3.323 kN) of 2-pile row nailed-slab system. Δk based on defined tolerable settlement.

Analysis of beams on elastic foundation using an equivalent modulus of subgrade reaction (k') which is a cumulative of the subgrade reaction modulus of the plate load test and Δk of the proposed approach, resulting in deflection fines in good agreement with observed deflections. Neglecting the lean concrete in designing the Nailed-slab System would give safer design.

In practice, the Nailed-slab System would be constructed by multiple row piles. Designing of the Nailed-slab System based on an analysis of the one row pile will produce a safe design. It is caused by higher pile group resistance and increases in slab stiffness according to multiple-row of piles installation. Besides, designing process will be less time consuming.

Further research can be conducted for different pile configuration pattern and the behavior of prototype of the Nailed-slab system.

VI. CONCLUSION

The observations and analysis on the deflection of the Nailed-slab System model have been performed. Additional subgrade reaction modulus (Δk) caused by the installation of the pile can be approximated by means of identifying the tolerable settlement. The displacement of pile head has been assumed to be equal to the slab deflection. Furthermore, for designing purposes, slab deflection is approached by making use of a tolerable settlement (δ_a). It can be noted that the increase in δ_a will decrease Δk.

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