http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 10 No 1 2025

RESEARCH ARTICLE

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

Anas Puri [1,*], Ferly Oktavia[2,3], Elizar[1], Dimas B.E. Dharmowijoyo[4, 5], Mujahid Ali[6], Liza Evianti Tanjung[7]

[1] Universitas Islam Riau, Department of Civil Engineering, Jl. Kaharuddin Nasution 113 Pekanbaru, Indonesia.
[2] Former Student of Graduate Program of Civil Engineering, Universitas Islam Riau, Jl. Kaharuddin Nasution 113 Pekanbaru, Indonesia.
[3] Universitas Maritim Raja Ali Haji, Department of Civil Engineering, Tanjung Pinang, Indonesia.
[4] Universiti Teknologi Petronas, Department of Civil Engineering, Perak Darul Rizduan, Malaysia.
[5]Universitas Janabadra, Department of Civil Engineering, Yogyakarta, Indonesia
[6]Silesian University of Technology, Department of Transport System Traffic Engineering and Logistics, ul. Akademicka 2A, 44-100 Gliwice, Poland.
[7] Universitas Muhammadiyah Sumatra Utara, Department of Civil Engineering, Medan, Indonesia.

* Corresponding author : anaspuri@eng.uir.ac.id
Tel.:+6285329582788; fax: -
Received: Sep 9, 2024; Accepted: Feb 26, 2025.
DOI: 10.24273/jgeet.2016.1.2.001

Abstract

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

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

Accepted Manuscript in Press

1. Introduction

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

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

The equivalent modulus of subgrade reaction is cumulative of the modulus of subgrade reaction of the slab (k) and additional modulus of subgrade reaction (Δk). The additional modulus of subgrade reaction based on the relative displacement between the pile and soils was used (Hardiyatmo, 2011). The development of the formula was based on static theory.

A new approach for practical purposes in designing the Nailed-slab System was proposed (Puri, et.al. 2012a). This approach considered that the pile friction resistance is fully mobilized and a tolerable settlement is addopted. The proposed method of analysis is applied on one row of the pile of the Nailed-slab. In the practice, the Nailed-slab will be constructed by multiple rows of piles. This system will have higher capacity and stiffness. Hence, designing the Nailed-slab System based on an analysis of the one-row pile will produce a safe design (Puri, et.al. 2012a; Puri, 2015).

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

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

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

where k_a' is the allowable equivalent modulus of subgrade reaction (kN/m^3), and SF_G is a global safety factor, k is the modulus of subgrade reaction from plate load test (kN/m^3), and Δk_m is the modified additional modulus of subgrade reaction. The Δk_m should be determined by Eq.(2).

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

where δ_a is the tolerable settlement of rigid pavement slab (m), f_s is the ultimate unit friction resistance of pile shaft (kN/m^2), A_s is the surface area of pile shaft (m^2), A_{ps} is the area of plate zone which supported by a single pile (m^2). The tolerable settlement of slab δ_a should not be higher than 5 mm.

Taking a δ_a value of a maximum allowable deflection of 5 mm tends to result in an over-estimated calculated deflection with an increase in SF_G (Oktavia, et.al., 2023). The shape of the *p*-δ curve is abnormal at low loads for all SF_G variations.

This paper is aimed to learn the prediction of the slab deflection by applying the allowable equivalent modulus of subgrade reaction on a 3-pile row nailed-slab system. The δ_a value is taken as the deflection of observations from previous researchers. Calculated slab deflections were compared with the observed deflections. The slab was loaded by concentric and ex-centric loadings.

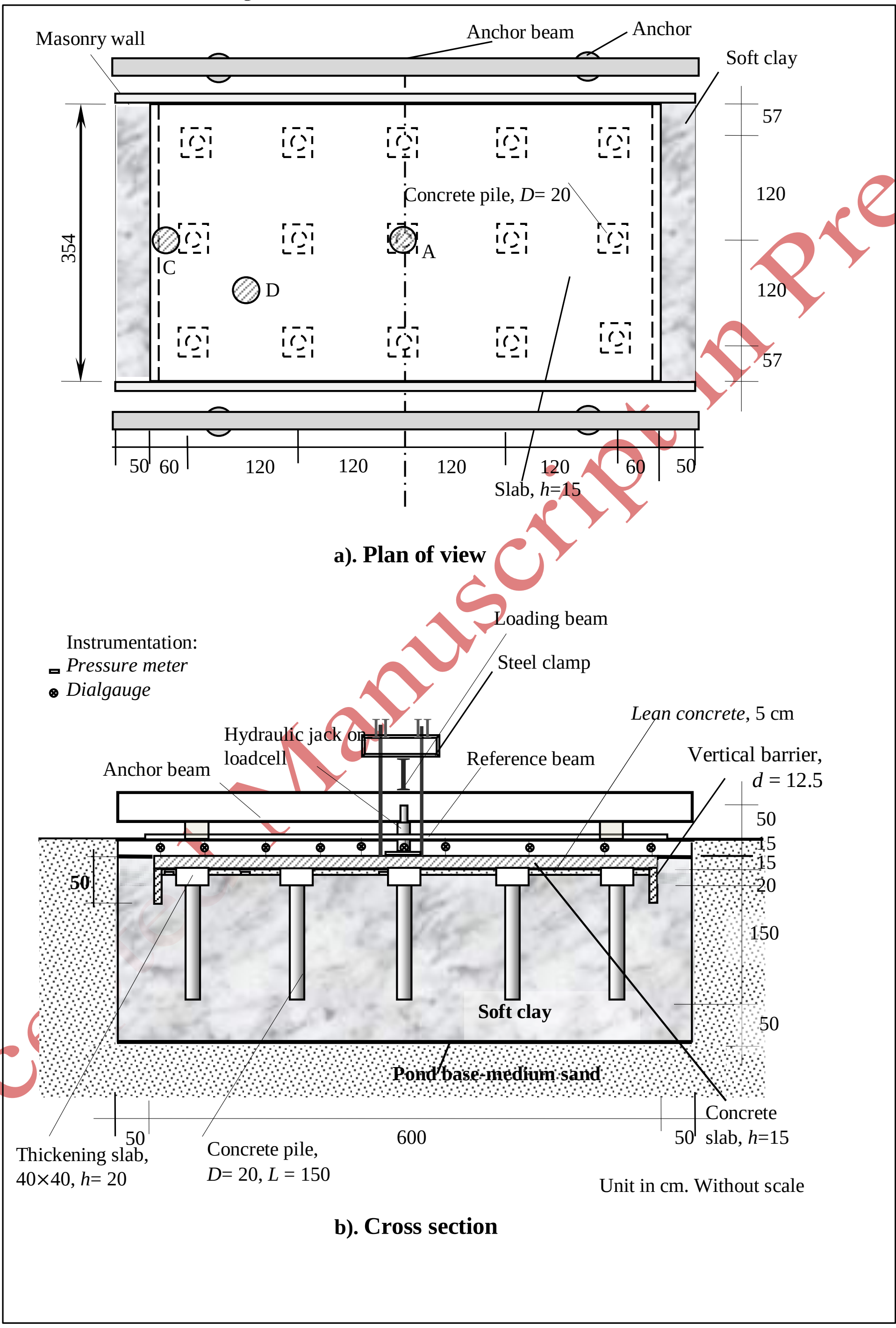

Fig. 1. Schematic diagram of the testing investigation (Puri, et.al. 2013b; Puri, et.al. 2014).

Accepted Manuscript in Press

2. Investigated 3-pile rows full-scale nailed-slab pavement system

Puri, et.al, (2013b) presented the detail of the procedure on 3-pile row full-scale Nailed-slab and briefly described also in Puri, *et.al.* (2013a). The single-pile full-scale nailed-slab was constructed on soft clay. The model was loaded by a hydraulic jack on the center of the slab. The loads were transferred to the slab surface by using a circular steel plate. Slab deflections were measured by dial gauge on the center-cross line of the slab and the corner of the slab. Figure 1 shows the schematic diagram of the testing investigation and Figure 2 presents photographs of the investigation (Puri, et.al. 2014).

The soft clay properties are presented in Table 1. The slab and piles were reinforced concrete. The concrete strength characteristic of the slab and piles was 29.2 MPa and 17.4 MPa respectively. The flexural strength of the slab was 4,397.6 kPa. The coefficient of subgrade reaction was 15,000 kPa/m based on the standard plate load test. The corrected coefficient was 3,750 kPa/m based on the dimension and shape of the slab (according to Das, 2011).

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

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

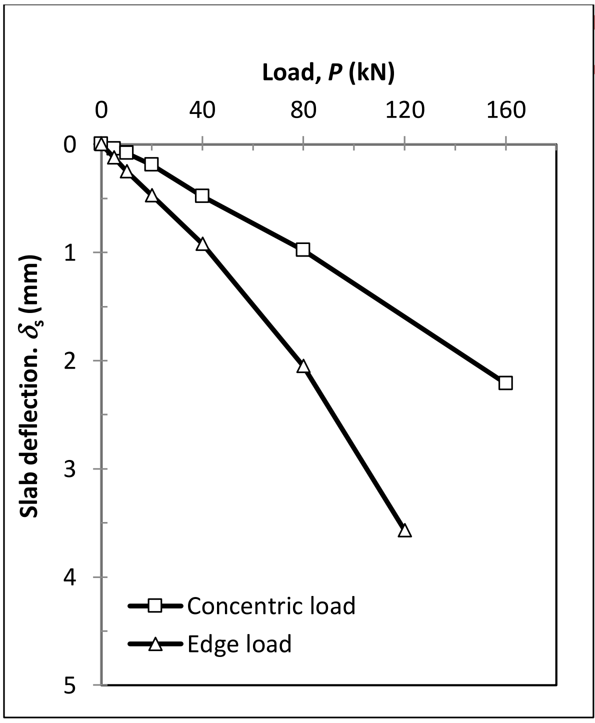

Fig. 3. *P-δ* relationship for loading tests of 3-pile row nailed slab under repetitive loadings for the 5th repetition (Puri, et.al. 2014).

The SF_G was varied by 1.0; 2.0; 2.5 and 3.0. An analysis of the deflection was calculated by the theory of Beams on the Elastic Foundation (BoEF). The BoEF analysis was conducted by using the "BoEF.xls software version 1.4". According to the limitation of BoEF, some simplification has to be done (Puri, 2015; Puri, et.al 2014), neglecting the lean concrete reaction modulus and slab thickening. Since the slab thickening was neglected, then the pile length was adjusted by adding the thickness of slab thickening with the initial pile length. The comprehensive analysis procedure is described in Puri, et. all (2013a), and Puri (2015). Even though the Nailed-slab Pavement System consists of many pile rows, only one pile row to be considered in analysis. Briefly, the analysis procedure as follows:

a) calculating the corrected coefficient of subgrade reaction of the soft clay under the slab (corrected due to the dimension and the shape of the slab—in this study, the correction based on Das method (Das, 2011),
b) calculating the modified additional modulus of subgrade reaction by using Equation (2) (the tolerable settlements (δ_a) were taken by using observed deflections),
c) calculating the allowable equivalent modulus of subgrade reaction by using Equation (1),
d) calculating the inertia moment of the slab,
e) input the required parameters into BoEF software,
f) investigate the results (output of the bearing pressure is not considered).

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

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

3. Results and discussion

3.1. Allowable equivalent modulus of subgrade reaction

The soil modulus of subgrade reaction for 1.20 m slab width was 4,500 kPa/m. The equation (5) was used to calculate the modified additional modulus of subgrade reaction due to single-pile installation under the slab; the results are shown in Table 2 by variation in safety factor. The tolerable settlements (δ_a) were taken by using maximum observed deflections. Allowable equivalent modulus of subgrade reaction is included in Table 2. It seems that the Δk_m and k_a' tend to decrease by increasing the loads because of the increase in slab deflection. The Δk_m and k_a' tend to decrease also by increasing the global safety factor, SF_G. Similar results were also found in the additional modulus of subgrade reaction and equivalent modulus of subgrade reaction which decrease by increasing the loads (Puri, 2017b; Puri, et.al. 2016). Increasing of *SF* in the additional modulus of subgrade reaction decreases the equivalent modulus of subgrade reaction (Puri, 2017b; Puri, et.al. 2016).

uscript in Press

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

No.	Load, *P* (kN)	δ_a (mm)	Δk_m (kN/m³)	*k'* (kN/m³)	k_a' (kN/m³) 1.00	2.00	2.50	3.00
1	5	0.04	32,016.34	35,901.31	35,901.31	17,950.66	14,360.52	11,967.10
2	10	0.08	16,008.17	19,893.14	19,893.14	9,946.57	7,957.26	6,631.05
3	20	0.19	6,740.28	10,625.25	10,625.25	5,312.63	4,250.10	3,541.75
4	40	0.48	2,668.03	6,553.00	6,553.00	3,276.50	2,621.20	2,184.33
5	80	0.98	1,306.79	5,191.76	5,191.76	2,595.88	2,076.70	1,730.59
6	160	2.21	579.48	4,464.45	4,464.45	2,232.23	1,785.78	1,488.15

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

No.	Load, *P* (kN)	δ_a (mm)	Δk_m (kN/m³)	*k'* (kN/m³)	k_a' (kN/m³) 1.00	2.00	2.50	3.00
1	5	0.12	10,672.11	14,557.08	14,557.08	7,278.54	5,822.83	4,852.36
2	10	0.25	5,122.61	9,007.58	9,007.58	4,503.79	3,603.03	3,002.53
3	20	0.47	2,724.80	6,609.77	6,609.77	3,304.89	2,643.91	2,203.26
4	40	0.92	1,392.01	5,276.98	5,276.98	2,638.49	2,110.79	1,758.99
5	80	2.05	624.71	4,509.68	4,509.68	2,254.84	1,803.87	1,503.23
6	120	3.57	358.73	4,243.70	4,243.70	2,121.85	1,697.48	1,414.57

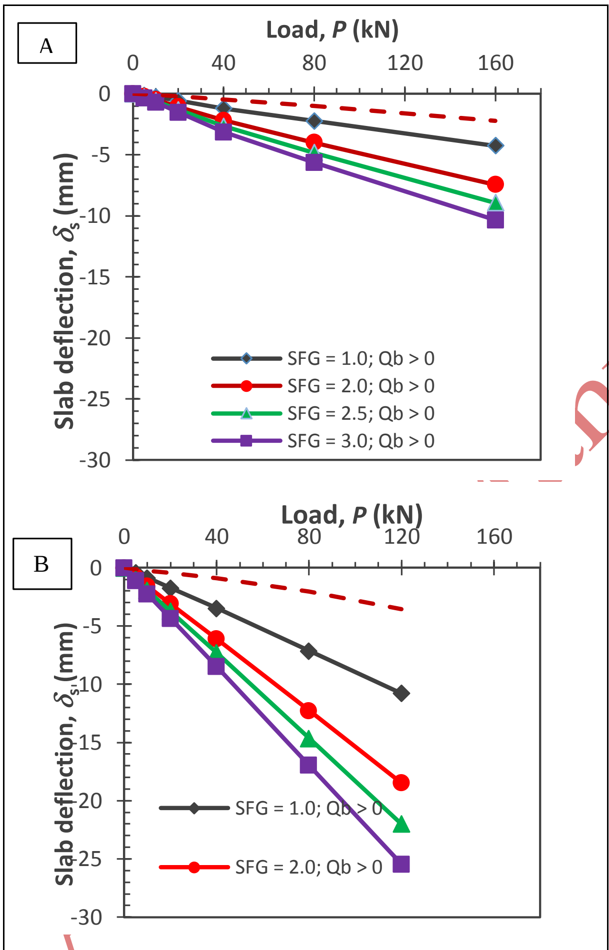

Fig. 4. *P*-δ relationship on loading point by variation of SF_G: a) concentric loads, b) edge loads.

3.2 Result of slab deflection

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

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

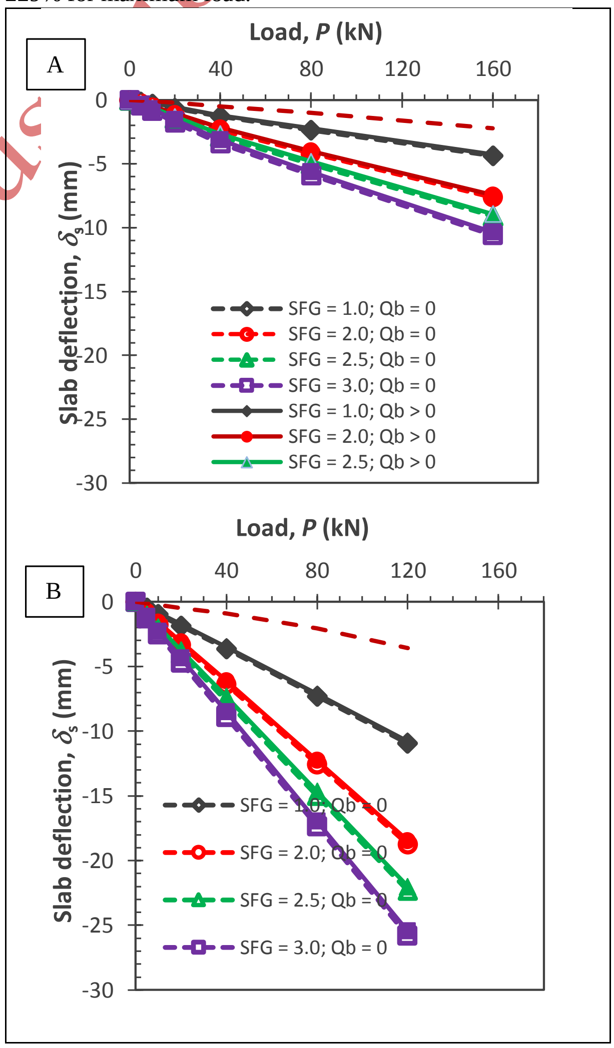

Fig.5. Effects of end bearing resistance Q_b on *P*-δ relationship by variation of SF_G: a) concentric loads, b) edge loads.

Manuscript in Press

It is also shown in Figure 5 that *P*- δ curves are in the elastic-plastic zone which is deferred with the theory. Higher the SF_G, elastic-plastic behavior is weaker. In this case, the Poisson's ratio did not influence the slab deflections (Puri, 2107). The BoEF analysis is two dimensional (2D). Poisson's ratio can influence the inner stresses. Hence, the failure criteria of the slab will increase. This means that the preliminary design by using Equation (4) will be in the safety zone.

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

4. Conclusion

This paper introduced the allowable equivalent modulus of subgrade reaction and the modified additional modulus of subgrade reaction. The additional modulus of subgrade reaction was calculated by Modified Hardiyatmo Method. The deflection of the slab was calculated by variation in the global safety factor and compared to the observed deflection.

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

Acknowledgements

Authors to thanks for supporting by Research Institute and Community Services (DPPM) with contract number 237/KONTRAK/P-PT/DPPM-UIR/07-2022 and the Laboratory of Civil Engineering Computational of Universitas Islam Riau.

References

Das, B. M., 2011. *Principle of Foundation Engineering 7th ed* (Stamford- Cengage Learning).

Dewi, S.H., Mildawati, R., Perdana, T. 2019. The Benefits of Adding Corn Stalk Ash as a Substitution of Some Cement Against of Compressive Strength Concrete , *Journal of Geoscience, Engineering, Environment, and Technology*: Vol. 4 No. 3 (Pekanbaru: UIR Press) 208-216 DOI: https://doi.org/10.25299/jgeet.2019.4.3.2966

Harinder, D. & Shankar, S. 2018. Experimental Study to Reinforce The Weak Subgrade Soil For Low-Volume Roads by Coir Geotextile Mats *Journal of Geoscience, Engineering, Environment and Technology* vol 3 no 1 (Pekanbaru: UIR Press) 1-7 DOI: https://doi.org/10.24273/jgeet.2018.3.01.882

Hardiyatmo, H. C., 2008. Nailed-slab System for Reinforced Concrete Slab on Rigid Pavement *Proc. of the National Seminar on Appropriate Technology for Handling Infrastructures* (Yogyakarta: MPSP JTSL FT UGM), M-1—M-7.

Hardiyatmo, H. C., 2009. Method to Analyze the Slab Deflection by Using Equivalent Modulus of Subgrade Reaction for Flexible Slab Structure *Dinamika Teknik Sipil* vol 9 (2) (Surakarta: Teknik Sipil-UNS), 149-154.

Hardiyatmo, H. C., 2011. Method to Analyze the Deflection of the Nailed Slab System *IJCEE-IJENS* vol 11 no 4 (Islamabad: IJENS Publisher), 22-28.

Hardiyatmo, H. C., and Suhendro, B., 2003. Pile Foundation with Thin Pile Cap as an Alternative to Solve Problems of Building on Soft Soils *Report of Competitive Grant Research of Higher Education* (Yogyakarta: Institute for Research and Community Service Gadjah Mada University).

Mildawati, R., Puri, A., Handayani, M.Z. 2022. Effects of Corn Stalks Ash as A Substitution Material of Cement Due to the Concrete Strength of Rigid Pavement *Journal of Geoscience, Engineering, Environment and Technology* vol 7 no 1 (Pekanbaru: UIR Press) 22-26 DOI: https://doi.org/10.25299/jgeet.2022.7.1.4681

Oktavia, F., Puri, A., Mildawati, R., 2018. Pengaruh Dimensi Tiang Mini dan Faktor Aman Terhadap Lendutan Pelat Terpaku Tiang Tunggal, *J. Saintis*, Vol. 8, No. 2, 11-21.

Oktavia, F., Puri, A., Elizar. (2023). Pengaruh Faktor Aman Global Modulus Reaksi Subgrade Ekivalen Izin Terhadap Lendutan Sistem Pelat Terpaku Tiga Baris Tiang. *Media Teknik Sipil*, 21(2), 39-48.
https://doi.org/10.22219/jmts.v21i1.25869

Puri, A., 2015. Behavior of Pavement of Nailed-slab System on Soft Clay *Dissertation Doctoral Program of Civil Engineering* (Yogyakarta: Universitas Gadjah Mada).

Puri, A., 2017a. Developing the Curve of Displacement Factor for Determination the Additional Modulus of Subgrade Reaction on Nailed-slab Pavement System *Int. Journal of Technology* vol 8 no 1 (Depok: Universitas Indonesia) 124-133.
http://www.ijtech.eng.ui.ac.id/old/index.php/journal/article/view/1688

Puri, A., 2017b. Effect of Safety Factors on The Calculated Deflection of 1-Pile Row Full Scale Nailed-Slab Pavement System Resting on Soft Clay Due to Concentric Loadings *ICoSET & ICoSEEH UIR 2017* (Pekanbaru: Universitas Islam Riau).

Puri, A., Hardiyatmo, H. C., Suhendro, B., and Rifa'i, A., 2011a. Experimental Study on Deflection of Slab which Reinforced by Short Friction Piles in Soft Clay *Int. Proc. of 14th Annual Scientific Meeting (PIT) HATTI* (Yogyakarta: HATTI), 317-321.

Puri, A., Hardiyatmo, H. C., Suhendro, B., and Rifa'i, A., 2011b. Contribution of Wall Barrier to Reduce the Deflection of Nailed-Slab System in Soft Clay *Int. Proc. of 9th Indonesian Geotech. Conf. and 15th Annual Scientific Meeting (KOGEI IX & PIT XV) HATTI* (Jakarta: HATTI), 299-306.

Puri, A., Hardiyatmo, H. C., Suhendro, B. and Rifa'i, A., 2012a. Determining Additional Modulus of Subgrade Reaction Based on Tolerable Settlement for the Nailed-slab System Resting on Soft Clay *Int. Journal of Civil and Environmental Engineering IJCEE-IJENS* vol 12(03) (Islamabad: IJENS Publisher), 32-40. http://ijens.org/Vol_12_I_03/129903-8585-IJCEE-IJENS.pdf

Puri, A., Hardiyatmo, H. C., Suhendro, B. and Rifa'i, A., 2012b. Application of The Additional Modulus of Subgrade Reaction to Predict The Deflection of Nailed-slab System Resting on Soft Clay Due to Repetitive Loadings *Int. Proc. of 16th Annual Scientific Meeting (PIT) HATTI* (Jakarta: HATTI), 217-222.

Puri, A., Hardiyatmo, H. C., Suhendro, B. and Rifa'i, A., 2013a. Application of Method of Nailed-slab Deflection Analysis on Full Scale Model and Comparison to Loading Test *Int. Proc. the 7th National Conference of Civil Engineering (KoNTekS7)* (Surakarta: UNS), G201-211.
https://sipil.ft.uns.ac.id/konteks7/prosiding/cover1.pdf

Accepted Manuscript in Press

Puri, A., Hardiyatmo, H. C., Suhendro, B. and Rifa'i, A., 2013b. Behavior of Full scale nailed-slab System with Variation on Load Positions", 1st *Int. Conf. on Development Infrasructure (ICID)*, Universitas Muhammadiyah Surakarta, Solo, 1-3 November 2013, 26-36.

Puri, A., Hardiyatmo, H. C., Suhendro, B. and Rifa'i, A., 2014. The Behavior of Nailed-slab System on Soft Clay Due to Repetitive Loadings by Conducting a Full-Scale Test *IJCEE-IJENS* vol 14 no 06 (Islamabad: IJENS Publisher), 24-30. http://ijens.org/Vol_14_I_06/147506-2323-IJCEE-IJENS.pdf

Puri, A., Hardiyatmo, H. C., Suhendro, B. and Rifa'i, A., 2019. Validating The Curve Of Displacement Factor Due To Full Scale Of One Pile Row Nailed-Slab Pavement System *Int. Journal of GEOMATE* vol 17 issue 59 (Mie: The Geomate International Society), 181-188. https://doi.org/10.21660/2019.59.65815

Puri, A., Oktavia, F., and Mildawati, R., 2018. Pengaruh Tahanan Ujung Tiang Dan Faktor Aman Terhadap Lendutan Pelat Terpaku Tiang Tunggal Pada Lempung Lunak Proceeding *20th SEAGC – 3rd AGSSEA Conference in conjuction with 22nd Annual Indonesian National Conference on Geotechnical Engineering* (Jakarta: HATTI), 529-533.

Puri, A., Oktavia, F., Dharmowijoyo, D.B.E., dan Ali, M., 2021. Prediction of Deflection of Single-pile Nailed-slab by Using the Allowable Equivalent Modulus of Subgrade Reaction in Case Additional Modulus from Modified Hardiyatmo Method, *3th Int. Conf. On Sustainable Infrastructure*, IOP Conf. Series: Earth and Environmental Science 832. https://iopscience.iop.org/article/10.1088/1755-1315/832/1/012022/meta#references

Puri, A, Suhendro, B. and Rifa'i, A., 2017. Effects of Vertical Wall Barrier on The Rigid Pavement Deflection of Full-Scale 1-Pile Row Nailed-Slab System on Soft Sub Grade *Int. Journal of GEOMATE* vol 12 issue 32 (Mie: The Geomate International Society), 25-29. http://dx.doi.org/10.21660/2017.32.6577

Somantri, A. K., 2013. Kajian Lendutan Pelat Terpaku pada Tanah Pasir dengan Menggunakan Metode Beam on Elastic Foundation (BoEF) dan Metode Elemen Hingga *Master's Thesis* (Yogyakarta: Program Pascasarjana UGM).

© 2025 Journal of Geoscience, Engineering, Environment and Technology. All rights reserved. This is an open access article distributed under the terms of the CC BY-SA License (http://creativecommons.org/licenses/by-sa/4.0/).

Accepted Manuscript in Press