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ANALYSIS OF SLAB DEFLECTION IN THE MODIFIED *CAKAR AYAM* PAVEMENT SYSTEM USING DISPLACEMENT FACTOR DERIVED FROM PURI'S GRAPH

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ABSTRACT: The pre-designed Modified *Chicken Claw* (MCA) pavement system can use the Hardiyatmo Method graph for pavements with a width of 7.5 m, where under the pavement slab, there are three claws with a diameter of 0.8 m and a height of 1.2 m, as well as a distance between the claws of 2.5 m. An equivalent modulus of subgrade reaction (k') was proposed to analyze the Nailed-slab pavement system. The displacement factor was used to determine the additional modulus of subgrade reaction due to pile installing (Δk). This paper aims to apply the curve of displacement factor from Puri's graph to calculate the deflection of the Modified *Cakar Ayam* (MCA) pavement system. Calculated deflections based on this curve were compared to the observed deflection. The deflection was calculated by using the Beam on Elastic Foundation method. Full-scale test result from the MCA pavement system was used. The concentric and edge loading points were considered. All calculated deflections were very over-estimated, around 260% to 665%, and higher than the allowable deflection of 5 mm in case of ignoring the end bearing resistance of a shell, except for concentric loads 40 kN (single wheel load). Calculated deflections by considering end bearing ($Q_b > 0$) were lower by more than 130% compared to calculated deflections by ignoring end bearing ($Q_b = 0$). In the case of MCA, the end bearing of the shell should be considered in the calculation. The displacement factor should be specially developed for MCA analysis.

Keywords: Cakar Ayam pavement, Displacement factor, Rigid pavement, Soft clay, Subgrade modulus

1. INTRODUCTION

Designing road pavement on a soft subgrade is also about a potential settlement that would occur during and after construction and how to maintain the deformation. Hence, it is needed such kind of system that can reduce the deflection of pavement. One of the systems that can be used is *Sistem Cakar Ayam* (chicken claw system). This system has two types: an original type, which uses the cylindrical concrete shell, and a modified type, which uses a cylindrical steel shell (called *Sistem Cakar Ayam Modifikasi*). In the Modified *Cakar Ayam* System (MCA), the utilization of a cylindrical steel shell was proposed by Ir. Maryadi Darmokumoro [1]. The use of steel cylinders is more practical on soft soils and swamps that do not require a working base. Very light steel cylinders weigh only about 35 kg. It is advantageous for soft soils because the self-weight of construction is the smallest. The reinforced concrete cylinders weigh up to 1,000 kg, which is not favorable for soft soils because they bear a large construction weight. In addition, the installation of concrete cylinders is more difficult, requiring a working base for heavy equipment in installing the concrete cylinders. The use of steel plates formed into cylinders/pipes is more practical in its mobilization because the steel plates are transported to the work site in sheet form, and then rolled to form a pipe according to the planned diameter at the work site. The plate connections can be welded or riveted. In addition, the base soil does not experience significant disturbance during pipe installation due to the thin shell. This CAM system also does not require heavy equipment during implementation and does not require temporary pavement for heavy equipment work platforms [3].

Some analysis methods of MCA were proposed, such as Suhendro's Chart, Hardiyatmo method by using Beam on Elastic Foundation (BoEF), and Hardiyatmo's Chart [2, 3]. The BoEF was used in MCA analyses such as Pempadi [4], Muhu [5], Afriliyani, et.al. [6], and Agustin, et.al. [7]. The MCA can be analyzed also by the 3D finite element method [1, 8-11].

Hardiyatmo [12] introduced a new method that was developed from the pavement of the MCA by changing the cylindrical foundation with short micro piles. This system is called the nailed-slab system. Replacing steel cylinders with short piles is to be more efficient in construction implementation. Driving short piles in soft soil and swamps is easier than steel cylinders. Hardiyatmo [13] proposed an analysis method for determining the additional modulus of subgrade reaction (Δk). The additional modulus of subgrade reaction is the additional modulus developed by a pile. Meanwhile, the modulus of subgrade reaction is the modulus considered from a slab. Puri et al. [14] modified the Hardiyatmo method by considering the tolerable deflection or allowable deflection of a pavement slab (δ_a) as an approach to safety construction. This modified method has good validation [15]. Puri [16, 17] proposed a curve of displacement factor ($\alpha = \delta_0/\delta_s$) for soft clay in calculating the Δk.

Hardiyatmo [13] used the displacement factor to determine the additional modulus of subgrade reaction. The displacement factor is the ratio of the relative displacement between piles and soils (δ_0) and the pile head settlement (δ_p). The pile head settlement is assumed to be similar to the slab deflection (δ_s). The inverse of the displacement factor is the ratio of δ/δ_0. Hardiyatmo [18] developed the curve of the δ/δ_0 ratios based on the full-scale test of a single pile in stiff clay. The pile and slab were connected by bolts. In this paper, the curve of the δ/δ_0 ratios based on a full-scale test of a single-pile nailed slab in soft clay is developed. The pile and slab were connected monolithically. The curve of the δ/δ_0 ratios is also presented as the curve of the displacement factor.

MCA can be designed by using Hardiyatmo's Chart [2, 3], or complex analysis using the finite element method [8-9, 11, 19-20]. Analysis using the additional modulus of subgrade reaction (Δk) is more practical in the nailed-slab pavement system. The application of this method on MCA is to know the reliability of that method.

2. RESEARCH SIGNIFICANCE

The Nailed-slab pavement system is a development of the MCA pavement system. Therefore, there are many similarities and differences between both systems. The difference is that the Nailed-slab pavement system uses a pile foundation as a nail. The MCA pavement system uses reinforced concrete cylinders or steel cylinders as claws. This research aims to apply the analysis method of the additional modulus of subgrade reaction (Δk) by using Puri's graph [16] to calculate the slab deflection of the MCA system. The Δk depends on the soil shear strength and the contact area of the soil with the pile. So that it can be known for its potential application to the MCA pavement system and to be a simpler analysis procedure for the MCA pavement system. Previous research did not implement the additional modulus of subgrade reaction (Δk) by using Puri's graph on MCA analysis.

3. EQUIVALENT MODULUS OF SUBGRADE REACTION

The analytical approach in determining the equivalent modulus of subgrade reaction (k') is given as follows [13, 14, 21]:

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

Where k: modulus of subgrade reaction from plate load test (kN/m^3) and Δk: additional modulus of subgrade reaction due to pile installation under the slab (kN/m^3). The modulus of subgrade reaction from a plate load test (k) is usually taken by using a circular plate, and it should be corrected to the slab shape of the nailed slab. The secant modulus is recommended. Hardiyatmo [13] proposed Eq. (2) in determining the additional modulus of subgrade reaction (Δk). The relative displacement between the pile and soil is considered.

$$\Delta k = \frac{\delta_0 A_s}{\delta_s^2 s^2}\left(a_d c_u + p'_0 K_d tan\phi_d\right) \quad (2)$$

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

Hardiyatmo [13] re-published the relation between δ_0/δ_s and slab deflection for a full-scale model while the pile and slab were connected by bolts. The pile diameter was 20 cm, and the length of the pile varied between 1.0 m and 2.0 m. Puri [16] proposed a curve of displacement factor ($\alpha = \delta_0/\delta_s$) as shown in Figure 1. The derivation and validation of Puri's displacement factor curve were provided in Puri [16]. This curve for soft clay, which the Nailed-slab System was a full-scale model while the pile and slab were connected monolithically. Then, Eq. (2) is rewritten as [22]

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

Equation (2) and Eq. (3) considered only the skin friction resistance of the pile. If the end bearing is considered in the analysis, the Δk can be arranged as

$$\Delta k = \frac{\alpha(f_s A_s + f_b A_b)}{\delta_a A_{ps}} \quad (4)$$

where f_s : pile ultimate unit skin friction resistance (kN/m^2) can be obtained by Eq.(5), f_b : ultimate unit end bearing resistance (kN/m^2) can be obtained by Eq.(6) for soft clay, A_b : pile base area (m^2), and δ_a : allowable deflection of slab (m). The δ_a is 5.00 mm for all types of *Cakar Ayam* pavement system to prevent cracks in slab concrete.

$$f_s = a_d c_u + p_0' K_d tg\phi_d \quad (5)$$

$$f_b = c_u N_c \quad (6)$$

where N_c : bearing capacity factor (non-dimensional) can be considered by Skempton (1951).

Slab deflection can be calculated by BoEF while the input modulus is k' from Eq. (1). Roark formula will be used for a finite beam.

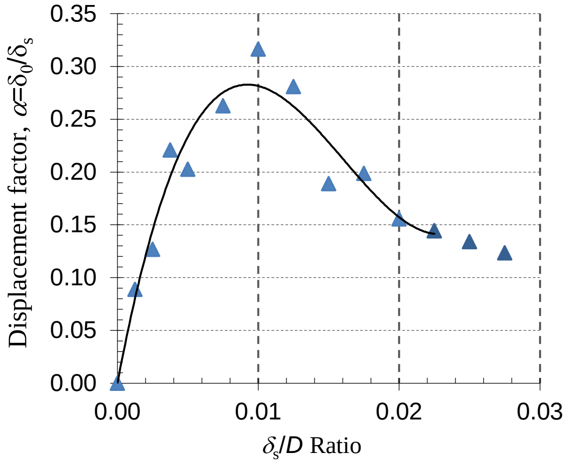


Fig. 1 The curve of the displacement factor α [16] for nailed-slab pavement system.

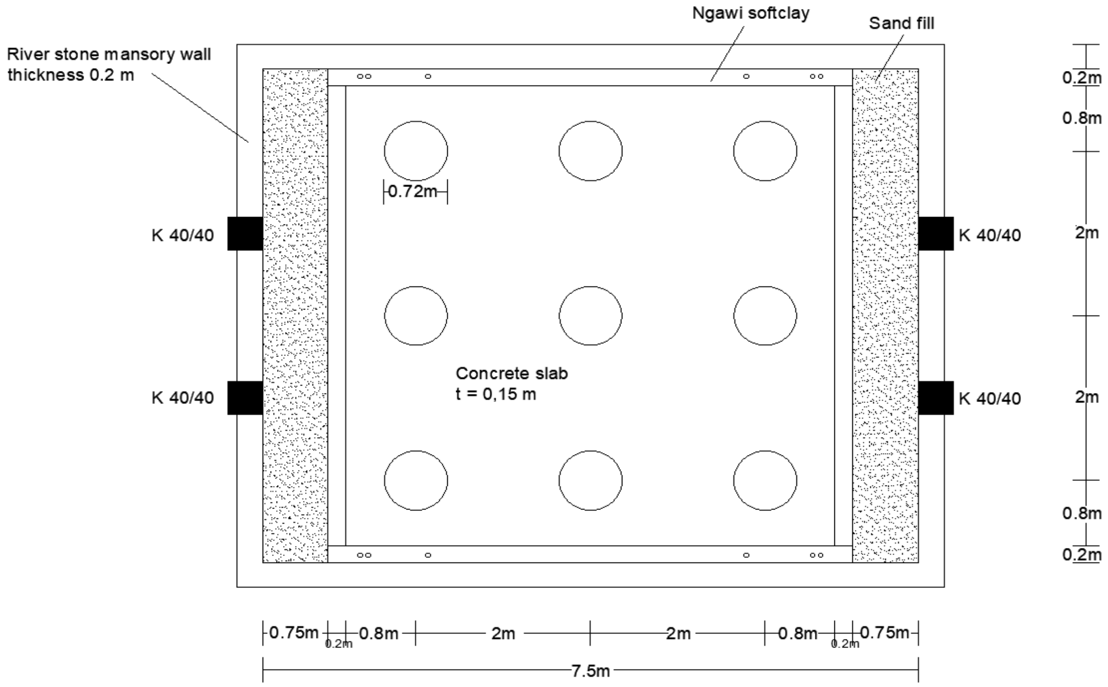
4. METHODOLOGY

4.1 Research Object

The research object was a full-scale model of the MCA from Setiawan [11]. The MCA consisted of a slab with 6.00 m x 6.00 m in width and length and 0.15 m in thickness. The slab was constructed with reinforced concrete. Concrete compression strength characteristic, f_c' was 32.16 MPa. The MCA was constructed in soft clay. Soft clay properties are presented in Table 1. The vertical modulus of subgrade reaction, k_v was taken from the Plate Load Test by using 30 cm in plate diameter. Nine cylindrical steel shells were installed under the slab and connected monolithically. Shell spacing was 2.00 m. Shell had dimensions 0.72 m in diameter, 1.015 m in height, and 1.4 mm in thickness. A schematic diagram of the MCA is presented in Figure 2. This system was loaded by vertical compression loading on point A (edge of the slab) and also on point D (concentric of the slab), as shown in Figure 3. Load variations were 0 kN, 20 kN, 60 kN, 100 kN. Loads were transferred to the slab surface by a steel plate 30 cm in diameter.

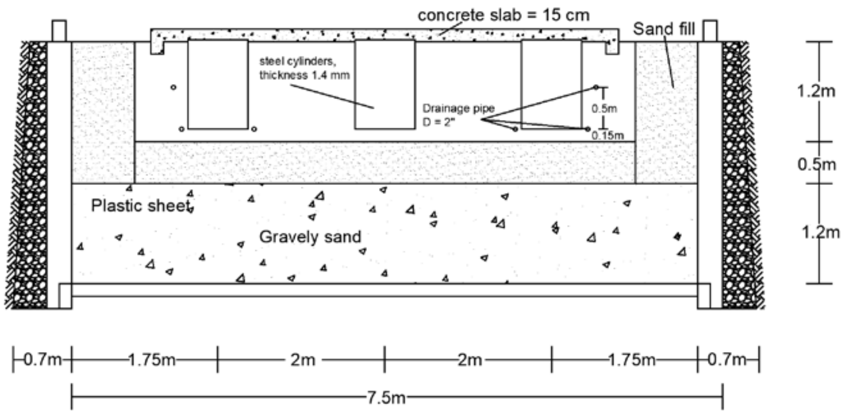
Table 1. Properties of clay based on field test [11]

No.	Properties	Value	Unit
1	Undrained cohesion (c_u)	15	kN/m^2
2	The degree of soil field density	92	%
3	Vertical modulus of subgrade reaction, k_v	5,498.4	kN/m^3
4	Soil classification (USCS)	CH	-



a) Plan view

Fig. 2 Schematic diagram of MCA [11].

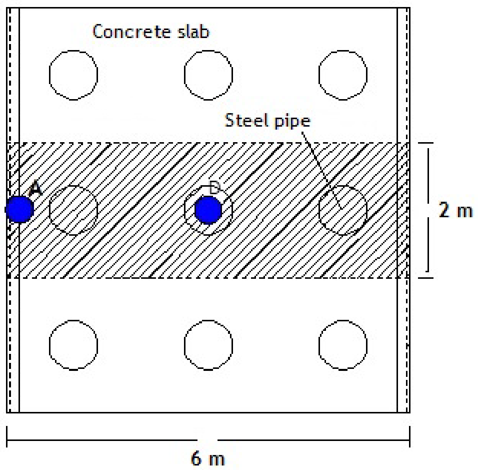


b) Cross-section

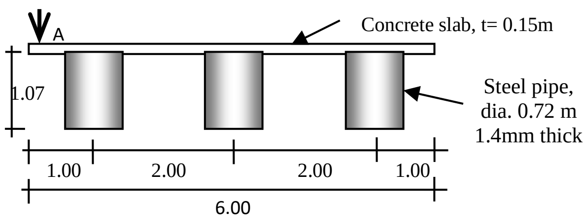
Fig. 2 *continues*.

4.2 Method of Analysis

Considered MCA in BoEF analysis was only one shell row as shown in Figure 3a. Simplification was done by neglecting the lean concrete, shell connector, and vertical wall barrier (Figure 3b). Deflection of the surface of the slab (δ_s) was taken from observation. From soil properties and MCA dimension, the *k*' was calculated. Slab deflection was calculated by inputting the *k*', MCA dimension, and properties to BoEF. Calculated deflection will be compared to observation results.



a) Plan of one shell row to be considered



b) Cross-section

Fig. 3 One shell row of MCA is to be considered in the analysis.

5. RESULTS AND DISCUSSIONS

5.1 Ignoring the End Bearing Resistance (Q_b = 0)

5.1.1 Equivalent modulus of subgrade reaction

The vertical modulus of subgrade reaction was corrected due to plate shape and dimension, according to Das [23]. Hence, the k_v was 641.48 kN/m^3. Considering the 2.00 m slab width, it was found that k = 1,282.96 kN/m^3. Based on soil cohesion c_u = 15 kPa, the adhesion factor a_d was 1,0 according to Tomlinson's curve in the McClelland graph (1974). Hence, the unit friction ratio f_s was 15 kPa. The surface area of shell shaft A_s was 2.30 m^{2,} and the slab area, which was supported by one shell s^2 was 4.00 m^2. Slab deflection δ_s for 20 kN load was 0.558 mm. By 0.72 m in shell diameter D, we found the ratio of δ_s/D = 0.000775. Then, the displacement factor α from Figure 1 was 0.05. By using Eq. (3), the additional modulus of subgrade reaction Δk was 772.85 kN/m^3.

Table 2. Modulus of subgrade reaction based on an observed deflection for Q_b = 0

a) Load point A [21]			
Load (kN)	δ_s (mm)	Δk (kpa/m)	*k*' (kpa/m)*
20	0,558	772,85	3.083,72
40	1,195	505,23	2.682,29
60	1,97	612,94	2.843,85
100	3,774	525,64	2.712,90
b) Load point D			
Load (kN)	δ_s (mm)	Δk (kpa/m)	*k*' (kpa/m)
20	0,383	450,39	1.733,35
40	0,617	559,16	1.842,12
60	0,841	769,17	2.052,13
100	1,445	716,26	1.999,22

* Multiplied by adjustment factor 1.5

According to Eq. (1), the equivalent modulus of subgrade reaction was 2,055.81 kN/m^3. Since the edge of the slab is equipped by a vertical wall barrier, the equivalent modulus should be considered an adjustment factor of about 1.5 [15]. So, the equivalent modulus of subgrade reaction k' = 3,083.72 kN/m^3. A similar step of calculation was also done to other loads and the calculation results are in Table 2.

5.1.2 Calculated deflection

Table 3 presents the calculated deflection results for all point loads. All calculated deflections were very over-estimated by more than 390%. Calculated deflections on point A (edge load) tend to be higher than the allowable deflection of 5 mm [10] for a standard single-wheel load of 40 kN. Over-estimated was caused by ignoring the end bearing resistance of the shell in determining the additional modulus of subgrade reaction Δk as in Eq. (2) and Eq. (3). It could also be because of neglecting the lean concrete, shell connector, and vertical wall barrier. It is suggested the maximum overestimated is less than 200% for more design efficiency. This calculation results were considered on one shell row of MCA, as shown in Figure 3a. In the field, MCA construction is built with many rows of claws, so the deflection will be reduced significantly. It means that Puri's graph (Figure 1) can be used to determine Δk for MCA, but an adjustment factor is needed. Figure 4 shows the P-δ relationship on the loading point A. Calculated deflections tend to be in the zone of elastic behavior, which is appropriate with its theory.

Table 3. Calculated deflection on load position for Q_b = 0

Load point A [21]			
Load (kN)	Calcaluted	Observed	Differentiation (%)
20	4,273	0,558	665,77
40	8,284	1,195	593,22
60	11,204	1,97	468,71
100	18,525	3,774	390,86
Load point D			
Load (kN)	Calcaluted	Observed	Differentiation (%)
20	3,619	0,383	844,91
40	4,901	0,617	694,33
60	5,831	0,841	593,34
100	8,729	1,445	504,08

The deflections along the slab for edge load are shown in Figure 5. Although calculated deflections were very over-estimated, it can be seen that the deflection shapes of calculated deflections were similar to the observed ones. For the standard single-wheel load of 40 kN, a maximum slab deflection of 8.85 mm is obtained. If the distance between the maximum and minimum slab deflection is equal to the width of the slab (6.0 m), then the angular distortion is very small which is 1.5 x 10^{-4}. This is advantageous for the pavement slab to keep the slab from cracking.

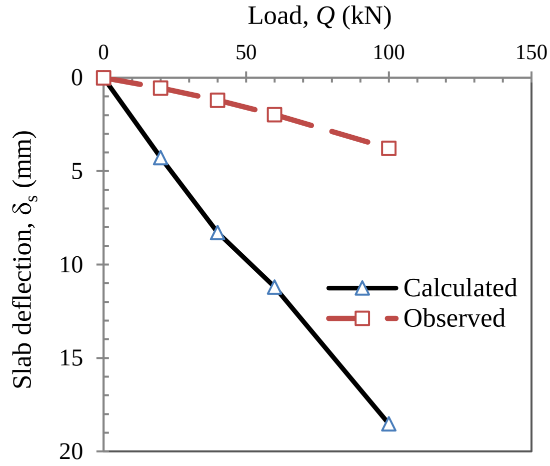


Fig. 4 P-δ relationship for edge load for Q_b = 0.

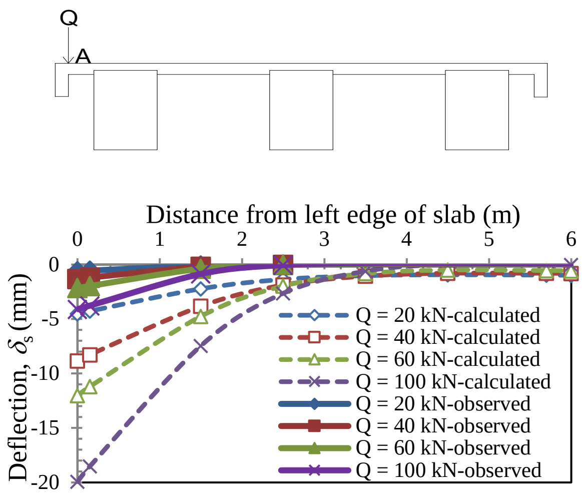


Fig. 5 Deflection along the slab for Q_b = 0 [22].

All calculated deflections for concentric loads (point D) were very estimated at more than 504%, but lower than the allowable deflection 5 mm ([10]) for a standard single-wheel load of 40 kN. Over-estimated was caused by ignoring the end bearing resistance of the shell in determining the additional modulus of subgrade reaction Δk as in Eq. (2) and Eq. (3). It could be also because of neglecting the lean concrete, shell connector, and vertical wall barrier. It means that Puri's graph (Figure 1) can be used to determine Δk. Figure 6 shows the P-δ relationship on the loading point D (concentric load).

The deflection along the slab is shown in Figure 7. Although calculated deflections were over-estimated, it can be seen that the deflection shapes of calculated deflections were similar to the observed ones. For the standard single wheel load of 40 kN, a maximum slab deflection of 4.90 mm and minimum slab deflection of 2.01 mm were obtained. If the maximum and minimum slab deflection distance is equal to the half-width of the slab (3.0 m), then the angular distortion is very small, which is 9.7 x 10^{-5}. This is advantageous for the pavement slab to keep the slab from cracking.

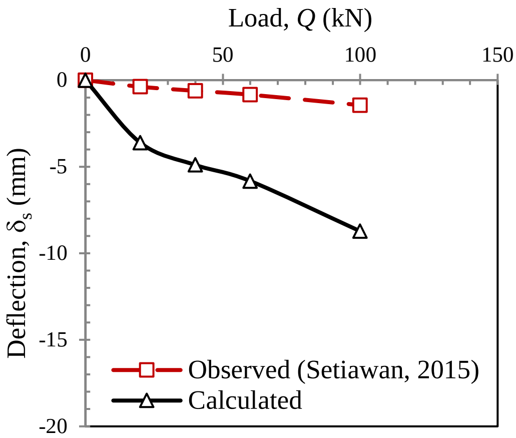


Fig. 6. *P*-δ relationship for concentric load for Q_b = 0.

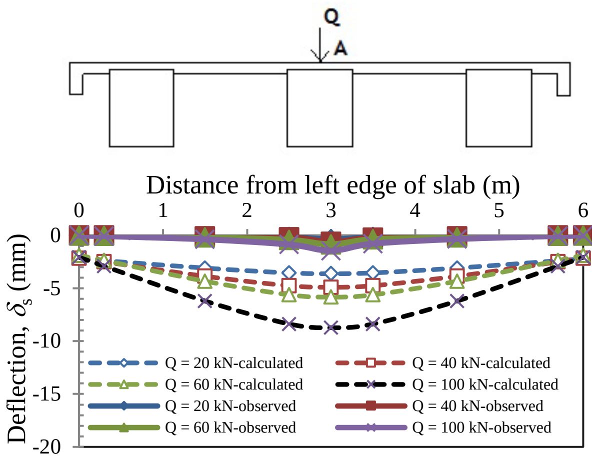


Fig. 7 Deflection along with the slab due to concentric loads for Q_b = 0.

5.2 Effects of end bearing resistance (Q_b > 0)

5.2.1 Equivalent modulus of subgrade reaction

According to the previous section, the k = 1,282.96 kN/m^3. Based on soil cohesion c_u = 15 kPa, the adhesion factor a_d was 1,0 according to Tomlinson's curve in the McClelland graph (1974). Hence, the unit friction ratio f_s was 15 kPa. The surface area of shell shaft A_s was 2.30 m^2, and the slab area, which was supported by one shell s^2 was 4.00 m^2. Slab deflection δ_s for 20 kN load was 0.558 mm for edge load (point A). By 0.72 m in shell diameter D, we found the ratio of δ_s/D = 0.000775. Then, the displacement factor α from Figure 1 was 0.05. By using Equation (4), the additional modulus of subgrade reaction Δk was 2,003.70 kN/m^3. According to Equation (1), the equivalent modulus of subgrade reaction was 4,929.98 kN/m^3 (after multiplied by adjustment factor 1.5 for edge loads since the edge of the slab is equipped by a vertical wall barrier [15]. A similar step of calculation is also done for other loads, and the calculation results are presented in Table 4.

Table 4 Modulus of subgrade reaction based on an observed deflection for Q_b > 0

c) Load point A			
Load (kN)	δ_s (mm)	Δk (kpa/m)	k' (kpa/m)*
20	0,558	2,003.70	4,929.98
40	1,195	1,309.86	3,889.23
60	1,970	1,589.12	4,308.12
100	3,774	1,362.77	3,968.60
d) Load point D			
Load (kN)	δ_s (mm)	Δk (kpa/m)	k' (kpa/m)
20	0,383	1,167.69	2,450.65
40	0,617	1,449.68	2,732.64
60	0,841	1,994.17	3,277.13
100	1,445	1,856.99	3,139.95

* Multiplied by adjustment factor 1.5

5.2.2 Calculated deflection

Table 5 presents the calculated deflection results by considering end bearing resistance, Q_b. All calculated deflections for edge loads (point A) were over-estimated by more than 260%, and higher than the allowable deflection of 5 mm. All calculated deflections for concentric loads (point D) were over-estimated by more than 320%, but tend to be lower than the allowable deflection of 5 mm. Over-estimated was caused by neglecting the lean concrete, shell connector, and vertical wall barrier. However, the end-bearing resistance of the shell was considered in determining the additional modulus of subgrade reaction Δk.

For more design efficiency, it is suggested that the maximum overestimated is less than 200%. This calculation result was considered on one shell row of MCA, as shown in Figure 3a. In the field, MCA construction is built with many rows of claws, so the deflection will be reduced significantly.

Figures 8 and 9 show the *P*-δ relationship on the edge and concentric loads' loading points, respectively. This figure compares the calculated deflection between the ignoring end bearing (Q_b = 0) and the considering Q_b (> 0). Calculated deflections by considering end bearing (Q_b > 0) are more realistic and tend to be closer to observed deflections. Calculated deflections by considering end bearing (Q_b > 0) were lower by more than 130% compared to calculated deflections by ignoring end bearing (Q_b = 0). Although calculated deflections were very over-estimated, it can be seen that the deflection shapes of calculated deflections tended to be similar to the observed ones. Calculated deflections tend in the zone of elastic behavior, which is appropriate with its theory.

Table 5 Calculated deflection on load position for Q_b > 0

Load (kN)	Calcaluted	Observed	Differentiation (%)
Load point A			
20	2.867	0.558	413.80
40	6.088	1.195	409.46
60	7.974	1.970	304.75
100	13.607	3.774	260.55
Load point D			
Load (kN)	Calcaluted	Observed	Differentiation (%)
20	2.658	0.383	593.99
40	3.509	0.617	468.72
60	3.966	0.841	371.58
100	6.082	1.445	320.90

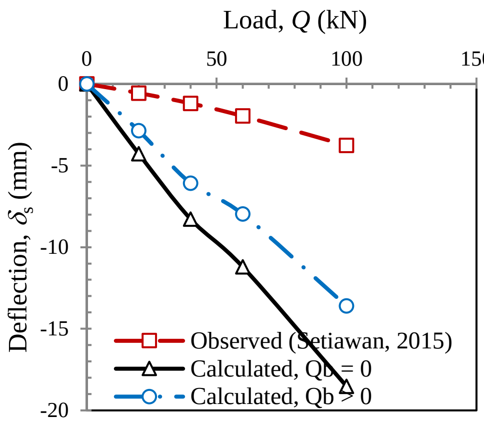


Fig. 8 *P*-δ relationship of edge load for Q_b > 0.

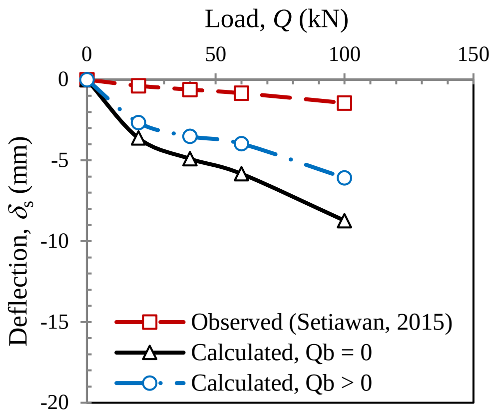


Fig. 9 *P*-δ relationship of concentric load for Q_b > 0.

The deflection along the slab is shown in Figures 10 and 11 for edge loads and concentric loads, respectively. Although calculated deflections were over-estimated, it can be seen that the deflection shapes of calculated deflections were similar to the observed ones for both edge loads and concentric loads. The results demonstrate that considering end-bearing resistance, Q_b > 0 improves deflection predictions. This finding can be utilized or integrated into a design procedure. The end bearing of the shell should be considered in the design analysis of MCA.

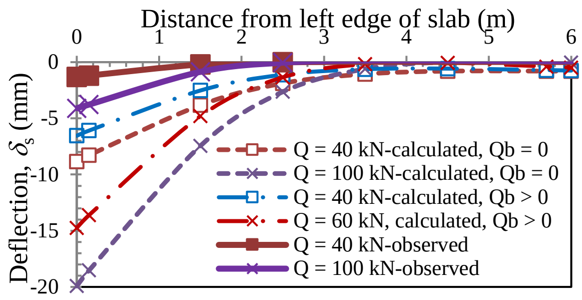


Fig. 10 Deflection along with the slab due to edge loads for Q_b > 0.

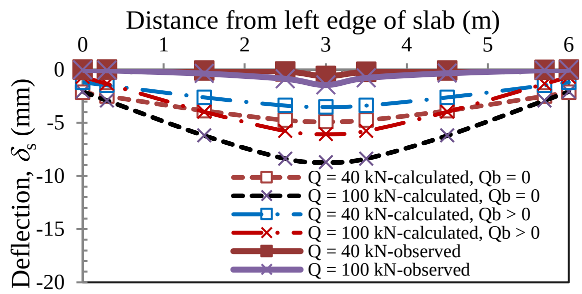


Fig. 11 Deflection along with the slab due to concentric loads for Q_b > 0.

The results of this study will have implications for the use of the additional modulus of subgrade reaction can be used for MCA pavement analysis. However, further research needs to be carried out to develop the curve of displacement factor for MCA.

6. CONCLUSION

In this paper, the analysis method of the additional modulus of subgrade reaction (Δk) by using Puri's graph was applied to calculate the rigid pavement deflection of *Cakar Ayam Modifikasi* (MCA) system. Calculated deflections were also compared to observed deflections. It is concluded that

1. All calculated deflections were very over-estimated around 390% to 665% in case ignoring the end bearing resistance of a shell in determining the additional modulus of subgrade reaction Δk. It could be caused by neglecting the lean concrete, shell connector, and vertical wall barrier. For concentric loads 40 kN (single wheel

load), maximum deflection is lower than allowable deflection. For edge load, the maximum deflection of 8.85 mm is a little bit higher than the allowable deflection of 5.0 mm, but it can be accepted for long-segment pavement. The analysis is based on a single pile row approach.

2. All calculated deflections by considering the end bearing of the shell were overestimated by around 260% to 593%. It could be caused by neglecting the lean concrete, shell connector, and vertical wall barrier. For concentric loads 40 kN (single wheel load), maximum deflection is lower than allowable deflection. For edge load, the maximum deflection is 6.55 mm, a little bit higher than the allowable deflection of 5.0 mm, but it can be accepted for long-segment pavement. The analysis is based on a single pile row approach.
3. Calculated deflections by considering end bearing ($Q_b > 0$) were lower by more than 130% compared to calculated deflections by ignoring end bearing ($Q_b = 0$).
4. The Puri's graph can be used to determine Δk for MCA analysis. In the case of MCA, the end bearing of the shell should be considered in the calculation. Designing MCA by using Puri's graph will be in the safety zone but an adjustment factor is needed.

Based on this study, it is recommended the maximum over-estimated less than 200% for more design efficiency. Further research needs to be carried out in developing the curve of displacement factor for MCA in soft clay for more accurate results of analysis.

7. ACKNOWLEDGMENTS

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