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The Behavior of the Flexible Plate – Supported with SiCC-Mortar Column on Expansive Soil

Agus Setyo Muntohar[1], Willis Diana[1*], Muhammad Yogma Tafalas[1], Nakosa Rafa Bimantara[1]

[1]*Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya, Tamantirto, Bantul, D.I. Yogyakarta, 55183, Indonesia*

Abstract. This paper provides the test results of the load-deformation test on a flexible plate, supported and unsupported by SiCC mortar columns in the laboratory setting. Two columns types were used in this experiment, a circular column (O-shape) and a column with head enlargement (T-shape). The main purpose of this study was to examine the heave of flexible plate due to the swelling effect and modulus of subgrade reaction under a loading-unloading cycle. The expansive soil was put into a testing container with a diameter and height of 550 mm and 1000 mm respectively. The clay thickness was 700 mm and the sand layer was compacted to 200 mm at the bottom of the container. The column diameter (D_c) was 50.8 mm (2 in.), and had a length of 500 mm. The height and diameter of the column head were enlarged to three times the column diameter ($3D_c$), which was about 152.4 mm (6 in.). Loading tests were performed after 8 days of saturation and 14 days of curing the column. The test results showed that installation of the column in support of the plate reduced the heave to about 16% and 22% respectively for the O-shape and T-shape column-support plates. The T-shape column-strengthened plate can enhance the modulus of subgrade reaction to about 203%. This result indicated significant improvement by the enlarged column head in carrying and transmitting the load to the soil.

Keywords: Deflection; Expansive soil; Flexible plate; SiCC column technique

1. Introduction

Building and road pavement damage on expansive clay soil has become a problem that needs serious treatment. The swelling and shrinking of expansive clay soil will have a considerable effect on the supported construction. Several methods can be applied to increase soil bearing capacity, such as material replacement or soil mixing, the alteration of chemical properties and the use of geosynthetics. Chemically, lime is widely used to stabilize expansive soil at a shallow depth of up to 1 m. Many investigators studied a deep mixing method using lime-columns or lime/cement- columns to strengthen expansive soil, e.g. Tonoz et al. (2003), Rao and Thyagaraj (2003), Hewayde et al. (2005), and Puppala and Pedarla (2017). These researchers explain that the lime or cement column technique can also serve as a mini pile foundation which functions to control the uplift force and deformation. The installation of columns from pozzolans into the subgrade is principally similar to the mini piles (Abiodun and Nalbantoglu, 2015). The columns system can

*Corresponding author's email: willis.diana@umy.ac.id, Tel.: 0274-387656; Fax.: 0274-387646
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increase the strength and decrease the deformation of the foundation caused by the swelling pressure of expansive soil (Tonoz et al., 2003; Hewayde et al., 2005; Muntohar and Liao, 2006). Active lime columns will absorb the soil moisture to produce hydration reaction in adjacent soil and surrounding column. The calcium ions from lime will penetrate into soil and migrate into the soil surrounding the column and will be enclosed by the lime-column (Abiodun & Nalbantoglu, 2015). The lime column, which is moistened with water, will react more rapidly than the column that is not moistened (Abiodun and Nalbantoglu, 2015; Puppala & Pedarla, 2017). When the columns are applied to support an upper structure, such as pavement, the system can be modeled as a piled-flexible plate (Core and Siddiqui, 2013; Diana et al., 2016; Puri, 2017; Huang et al., 2017).

The previous research, e.g. Abiodun and Nalbantoglu (2015), Damoerin et al. (2015), Tonoz et al. (2003), Hewayde et al. (2005), Muntohar and Liao (2006), mainly used lime or cement columns as a form of deep mixing stabilization. Those studies of lime or cement column were applied as a foundation system for flexible pavement on expansive clay. Hence, this paper introduces a new foundation system for flexible pavement to control the soil heave and enhance the load carrying capacity of the pavement. The purpose of this research is to study the characteristics of a flexible plate supported by the columns on expansive soil as a foundation system.

2. Experimental Methods

2.1. Materials

Clay soil was used as the basic material in the testing process. The consistency limits of the clay were 94.4%, 34.6%, and 59.8% respectively for the liquid limit, plastic limit, and plasticity index. Table 1 presents the geotechnical properties of the soil, and Figure 1 shows the grain size distribution of the soil. The soil is classified as high-plastic clay (CH). The swelling potential of the compacted specimen at maximum dry density (MDD) and optimum moisture content (OMC) states was 13%, and the swelling pressure was 140 kPa which was determined by Method C of ASTM D4546 (ASTM, 2008).

Table 1 Geotechnical Properties of the soil

Measurement	Value
Specific Gravity	2.61-2.68
Standard Proctor Compaction:	
Maximum dry density, MDD	12.2 kN/m^3
Optimum moisture content, OMC	27%
Shear strength (*CU* triaxial test)	
Effective cohesion, *c*'	1.2 kPa
Effective internal friction angle, ϕ'	13.8^o
Secant modulus of elasticity, E_{50}	3 – 13 MPa

The SiCC cemented materials were registered as patent P00201304681. The SiCC mortar was mixed with SiCC, sand, and water with the weight ratio of 1:1:2, and the water–binder ratio of 0.6. The compressive strength and secant modulus of the elasticity of the SiCC mortar were 517 kPa and 8.8 MPa respectively at 7 days age.

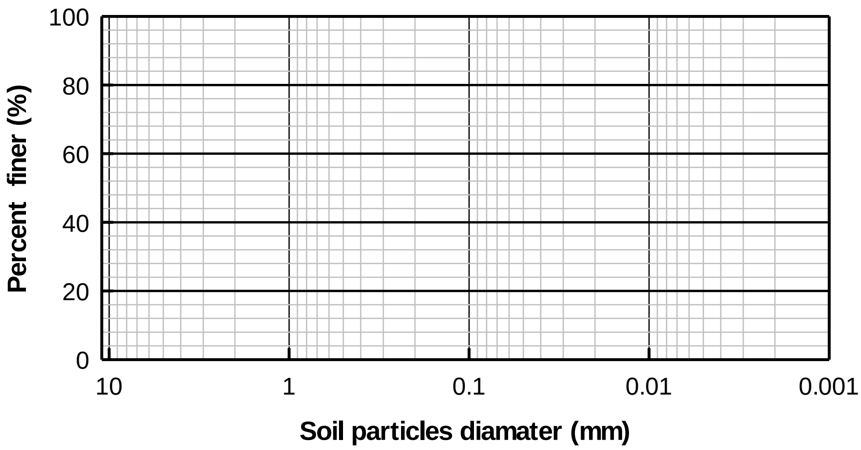

Figure 1 Grain size distribution of the soil used

2.2. Experimental Setting and Testing Procedure

The expansive soil was put into a testing container with a diameter of 550 mm and a height of 1000 mm. The testing container consisted of compacted expansive soil, which was compacted at 95% MDD. The soil thickness was 700 mm and was compacted gradually at every 100 mm thickness level using a drop-weight hammer weighing about 10 kg. Sand was compacted at the bottom of the container, the thickness of which was 200 mm (Figure 2a). The test was prepared based on three conditions, i.e. a test containing soil as a comparison, soil strengthened by O-shape column, and soil strengthened by T-shape column. The O-shape column is circular section (Figure 2b), and the T-shape column is the circular column with an enlarged column head (Figure 2c). The column diameter (D_c) was 50.8 mm (2 in.) with a length of 500 mm (Figure 3). For the T-shape column, the height and diameter of the column head were enlarged three times that of the column diameter ($3D_c$), about 152.4 mm (6 in.). The SiCC mortar was poured into the column hole (cast in place) which was drilled by a hand auger. A flexible plate made from 5 mm thick plexiglass and a diameter of 254 mm (10 in.) was placed on the ground and screwed to the column to ensure it's monolithic at the center of plate (see also Figure 3). The use of the flexible plate in the laboratory model was suggested by Hardiyatmo (2009). The investigation includes the plate heave due to swelling, and deflection due to loading-unloading tests.

After the column had been installed, the container was soaked with water for at least four days to allow the soil to reach final swelling. The swelling was measured from the dial gauge at the frame (see Figure 3). Three dial gauges were installed on the plate (DG-1, DG-2, DG-3), and one gauge was installed on the soil surface (DG-4) as described in Figure 3b. The DG-1 and DG-3 plates were located 100 mm from the center of the plate, while the DG-4 plate was placed 300 mm from the center. The load was added at the center of the plate. The loading test was performed after the column reached 14 days of curing. In this investigation, loading and unloading was conducted as a cycle, and was applied by increasing the weight gradually until it reached a maximum load (1.38 kN) or caused a failure. Hereafter, unloading was applied by reducing the weight incrementally to zero.

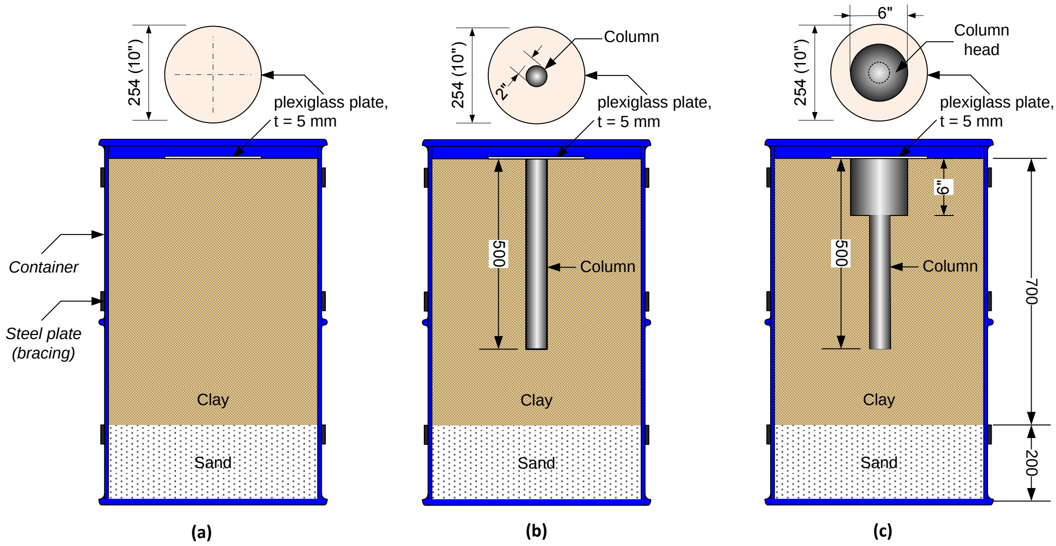

Figure 2 The sketch of the model: (a) soil; (b) O-shape column; (c) T-shape column

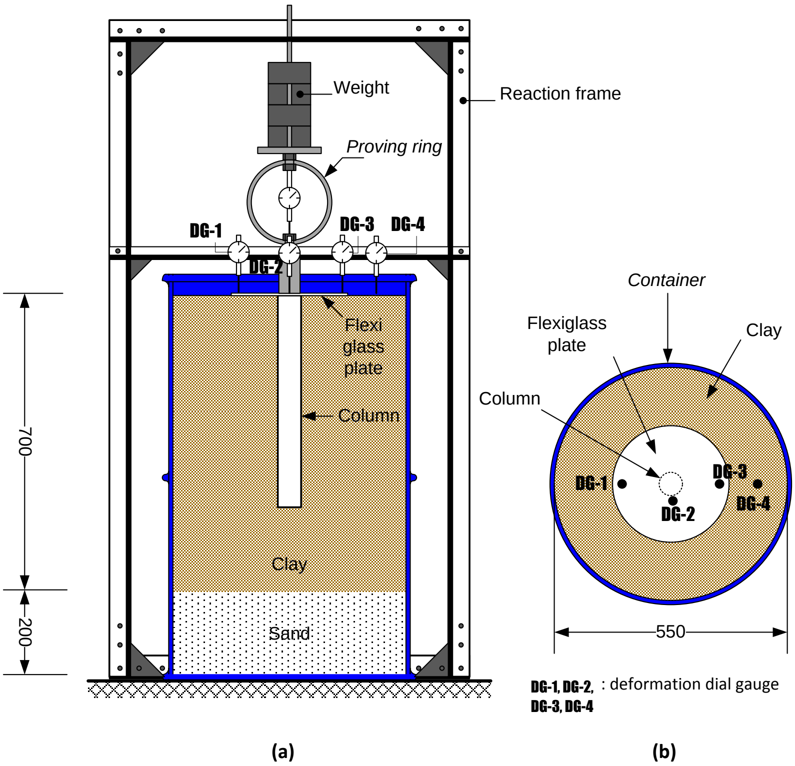

Figure 3 The loading frame and experiment set up: (a) cross section view; (b) plan view

3. Results and Discussion

3.1. The Heave due to Swelling

During the swell test, the soil was inundated continuously underwater for four days. The inundation allowed the soil to swell freely. This swelling resulted in the deflection of the plate and was measured at particular points as indicated in Figure 3. The uplift deflection of the plate is known as the heave. Figure 4 shows the plate heave due to the swelling of untreated (Figure 4a) and treated soil with the O-shape and T-shape columns (Figure 4b and 4c). In general, the heave increases with the elapsed time. Typically, the initial heave slowly increases, then steeply increases (primary heave), and finally slightly increases once more (final heave). The figure shows that the time to reach the initial, primary, and final heaves varied among the plates without and with column supports. Muntohar and Hashim (2005) mentioned in their study that the primary heave or swelling almost completed in 24 hours.

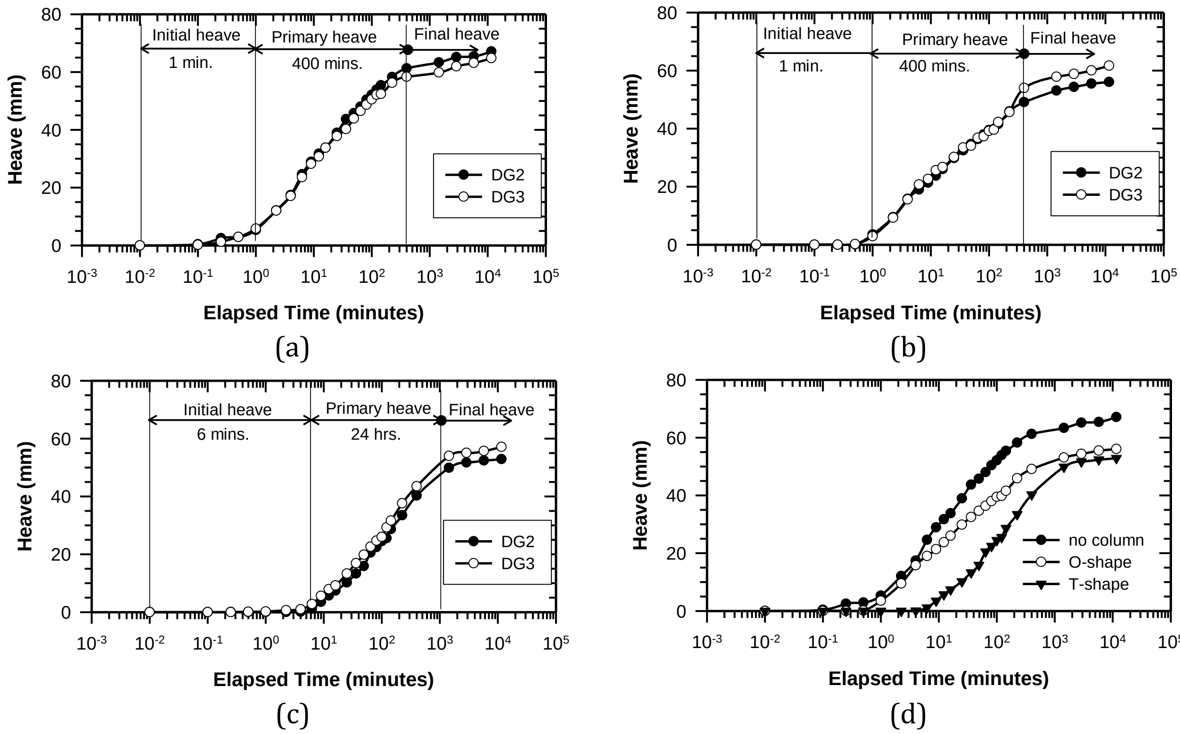

Figure 4 The change of plate heave with elapsed time: (a) the unsupported plate; (b) the supported plate with the O-shape column; (c) the supported plate with the T-shape column; (d) the heave comparison at the center of the plate (DG-2)

In this research, the initial and primary heave of the unsupported plate and the O-shaped supported-plate occurred in 1 minute and 400 minutes respectively. However, the final heave of the O-shaped column-supported plate was smaller than the unsupported plate. This phenomenon indicates that the cations (Ca^{2+} and Si^{2+}) in SiCC mortar-columns did not migrate into the soil surrounding the column. As expected, the migration of the cations inhibits the rate of swelling and reduces the final swelling due to cation exchange (Tonoz et al., 2003; Abiodun and Nalbantoglu, 2015).

A different behavior is shown for the T-shape column-supported plate (Figure 4c). The initial heave and primary heave were reached in 6 minutes and 1440 minutes (24 hours) respectively for initial and primary heave. This delay might be attributed to the enlargement of the column head for the T-shaped column. This enlargement might retain the water from infiltrating the sub-surface. Figure 5 indicates that the water content near the T-shape column is the lowest. On the other hand, Muntohar (2006) explained that the swelling was controlled by the weight of the structure on the expansive soil. A heavyweight structure will reduce the swelling and uplift pressure. As shown in Figure 2, the enlargement of the column head increases the volume and weight of the column, and therefore, it might be hampering the rate of the swelling and the reduction of the heave.

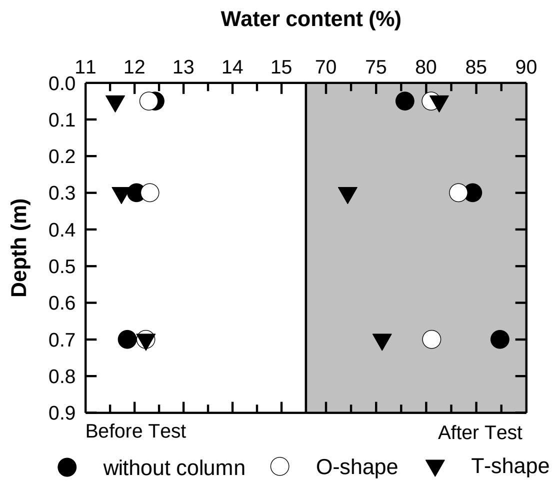

Figure 5 The variation of water content due to inundation on the ground surface

Figure 4d indicates that the installation of the column in support of the plate reduced the heave from 67 mm to 56 mm and 52 mm respectively for the unsupported, O-shape and T-shape column-support plate. The final heave of the T-shaped column is slightly different than the O-shaped column-support plate. This was because the columns were still constructed in the active zone. The column acts as a floating-pile in which the soil-column interaction is only mechanically improved, but the heave remains during swelling (Muntohar, 2014, Diana et al., 2016). Upon clay wetting, vertical-swelling pressure was developed that had a tendency to push the foundation upward and therefore, retracted the micropiles from the surrounding sand (Nusier and Alawneh, 2004). Soundara and Robinson (2017) noted that the uplift pressure, due to the swelling pressure, was restrained by the interface of shear stress along the column of the micropile. The T-shape column had a greater shaft than the O-shape column. As a result, the heave of the T-shape column-support plate had a higher shear stress interface and resulted in a smaller heave.

3.2. Load and Deflection Behavior

After swelling completed, the loading and unloading test was applied to the flexible plate system. Figure 6 shows the pressure and deflection of the plate due to loading-unloading cycle. In general, the plate deflection increased with the increase in applied pressure or workload on the plate. Figure 6a shows that the unsupported plate experiences failure after the applied pressure reaches 26 kPa (see also Figure 7). At this stage, cracks were observed on the plate; the loading was discontinued, and unloading was initiated. Installing the columns increased the load capacity of the plate to the maximum pressure. Figure 6b shows the pressure and deflection of the O-shape column supported plate. The maximum deflection at the middle plate is 29.18 mm. Furthermore, the deflection of the plate supported by the T-shaped column is 11.43 mm (Figure 6c). The result showed that the plate reinforced by the T-shaped column reduced the deflection by about 2.5 times.

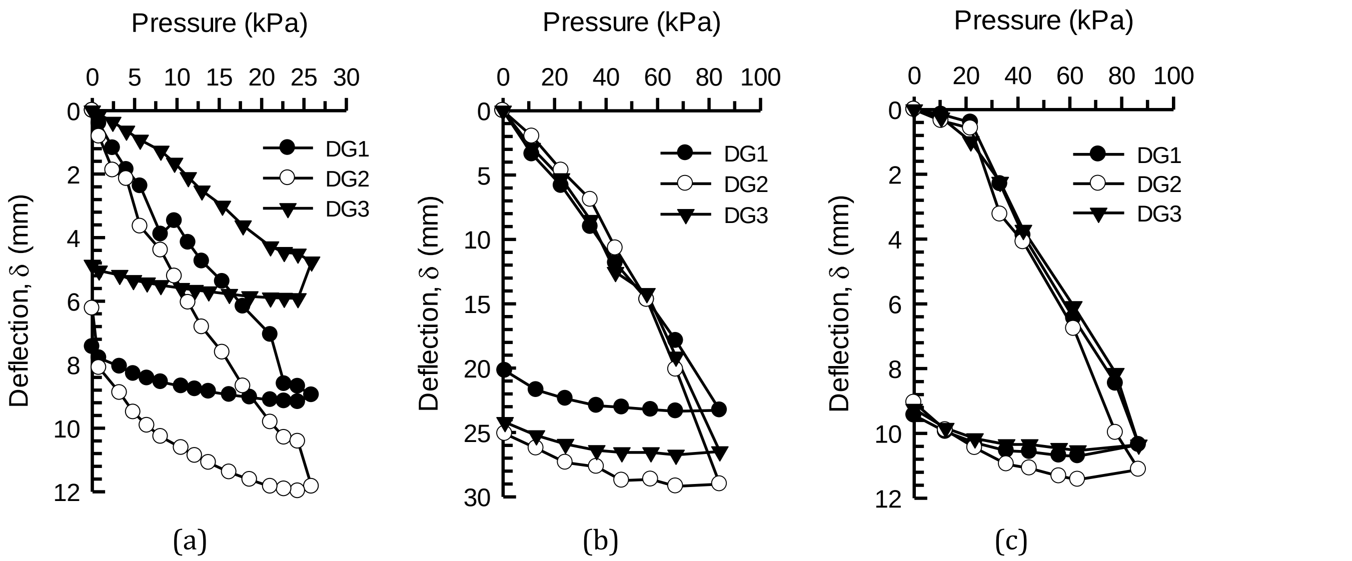

Figure 6 The pressure and deflection relationship at the middle of the plate: (a) the unsupported plate; (b) O-shape; (c) the T-shape

Figure 7 shows the deflection of the unsupported and supported plate at its maximum applied load. In Figure 7, the maximum pressure for the unsupported plate was only 25.61 kPa, which was the smallest pressure among the O-shape and T-shape columns-supported plates. The column used in this study can be categorized as a floating pile. The mechanism of load transfer to the column was restrained by the shaft friction of the column. Hence, the load carrying capacity of the column depends on the diameter of the column; the larger the diameter, the higher the load carrying capacity is, and the area ratio decreases. The enlargement of the columns head has a larger contact area (Liu et al., 2012), and as a consequence, the area ratio decreases. Thus, a greater load on the plate will be transmitted to the column. This result was confirmed by Malekpoor and Poorebrahim (2014). When the area ratio decreases, the load intensity of the specimens increases significantly. This concludes that the enlargement of the column head is capable of increasing load or column efficiency in receiving and forwarding the loads to the surrounding soil. It is beneficial to reduce costs by enlarging the column head instead of increasing the diameter of the whole column.

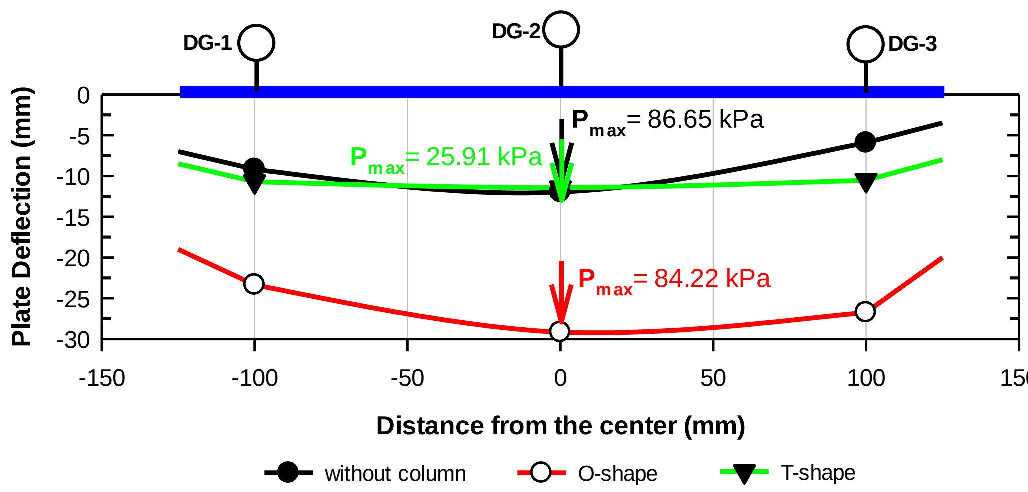

Figure 7 Plate deflection at the maximum applied load

Commonly, the modulus of subgrade reaction (k) represents the load and deformation relationship. The k value is defined as the average ratio of pressure to elastic deformation for the series of loads applied (ASTM, 1997). Table 2 presents the modulus of subgrade reaction for the unsupported plate and the supported plate with O-shape and T-shape column types. It is clearly observed that the addition of the O-shape column increases the k value slightly from 3.02 MPa/m to 3.56 MPa/m. The T-shaped column-strengthened plate can enhance the k value by three times, from 3.02 MPa/m to 9.14 MPa/m. A similar mechanism has been discussed by Puri (2017), whereby an additional modulus of subgrade (Δk) from the piles reduces the deflection of the plate.

Table 2 Modulus of subgrade reaction (k)

Test	Average Elastic Deflection, Δe (mm)	Pressure (kPa)	k (MPa/m)	Heave at center (mm)
Unsupported plate	8.57	25.91	3.02	67.09
O-shape column	23.66	84.22	3.56	56.05
T-shape column	9.48	86.65	9.14	52.86

The T-shape column-strengthened plate can enhance the modulus of subgrade reaction (k) by about 203%, and reduces the heave by about 22%. The results in Table 2 strongly indicating that increasing the value of k will reduce the heave in the plate-column system. Increasing the value of k can be attributed to the increase in the internal friction angle of the composite SiCC mortar and soil as indicated by Damoerin et al. (2015). Moreover, this result indicates significant improvement by the enlargement of the column head in carrying and transmitting the load to the soil. However, to obtain a maximum modulus of subgrade reaction, the enlargement of the column head is limited by column spacing, the length to diameter ratio, and the connection or joint system between the column and slab (Liu et al., 2012; Budiman et al., 2015).

4. Conclusion

This laboratory experiment was conducted to evaluate the heave and load deflection of the flexible plate supported with SiCC mortar columns. Two types of columns were used, an O-shape and T-shaped column. In general, this research shows that SiCC column-supported plates on expansive clay can reduce the heave and increase the load carrying capacity. In general, the heave increases with the elapsed time. Installation of the column to support the plate reduces the heave at about 16% and 22% respectively for the O-shape and T-shaped column-support plate. The reduction of the heave can be attributed to the mechanically effect instead of the migration of cations from the SiCC into the soil. The addition of the O-shape column increases the modulus of subgrade reaction slightly by about 18%. However, the T-shape column-strengthened plate can enhance the modulus of subgrade reaction (k) by about 203%. This result indicates a significant improvement by the enlargement of the column head to reduce the heave and carrying and transmitting the load to the soil. However, further study for both large scale and numerical models are needed to confirm this concluding remark.

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