A FORMULA FOR THE INCREASE OF SHEAR RESISTANCE OF SOFT TO MEDIUM COHESIVE SOILS DUE TO REINFORCEMENT WITH PILES (AN EXPERIMENT WITH LABORATORY MODELING OF PILE-SOIL INTERACTION)

Rusdiansyah

Abstract

An experiment with laboratory modeling of pile-soil interaction had been performed to investigate the capacity of pile as ground reinforcement when the piles were inserted into cohesive soils. A group of model piles were tested in soft to medium consistency of cohesive soils. A formula had been established to represent the lateral capacity of piles when the soils were subjected to a test similar with direct shear test. The formula contained a modification factor, Fk, to an existing formula derived from NAVFAC DM-7 (1971), in which the modification factor, Fk, was mainly influenced by the depth of pile insertion, the spacing distance between pile, the number of piles in row, and the diameter of piles.

Keywords : *pile-soil interaction, soil reinforcement with piles, slope stability, ground improvement, laboratory modeling*

1. INTRODUCTION.

Currently, there are many methods of soil reinforcement have been used on soft to medium soils to increase the shear strength of the soils. One of the methods of soil reinforcement used effectively to increase the stability of slopes and soil embankments above soft soil is using vertical piles inserted into the soil, in which the piles are acting as lateral resistance against shear sliding. In Indonesia, this system of soil reinforcement had been used widely in the past in the form of wooden and concrete mini piles with diameter 7.5 cm to 25 cm, driven vertically or slightly inclined on natural slopes that have been suspected to be in danger of sliding; or the piles were driven into the relatively soft soil under highway embankments, to increase the stability of the embankment as given in Figure 1.

The use of this method of piles as reinforcement in natural slopes in the past were also found to give more efficient solution than other methods of soil reinforcements, because this method could be applied without jeopardizing the existing stability of the slope, which was already very critical in the first place (de Beer and Wallays, 1970; Ito, et. all., 1981).The use of wooden piles to improve stability of embankment on top of soft soils were also popular in Sweden, while the use of bigger concrete bored piles, up to 1.50 m in diameter, were more popular in Europe and America to increase the stability of natural slopes of stiffer soils (Bulley, 1965).

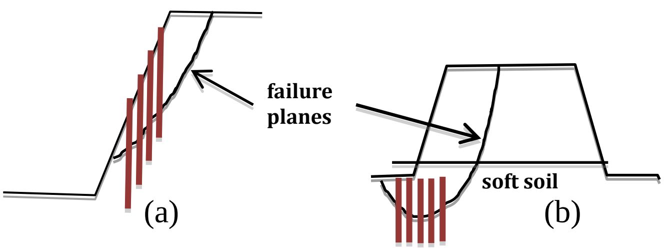


Figure 1. Typical soil reinforcement with piles acting as resistance against sliding.
(a). Piles acting as dowels against lateral sliding on natural slope.

*Lecture of Civil Engineering, Lambung Mangkurat University (ULM) Banjarmasin, Indonesia
Email : rusdiansyah74@ulm.ac.id. Phone : +6281348754958

(b). Piles acting as resistance against lateral sliding in soft soil under embankment.

Several studies had been performed in the fields by Mochtar (2011), in which the installment of vertical piles had proven to increase the stability of highway embankments and natural slopes. Mochtar (2011) also mentioned that in many cases on embankment on soft soils, the use of sheet piles as retaining wall might not be appropriate, because overall stability of the embankment (with sliding plain reaching beyond the bottom end of the sheet piles) should be the governing factor of the embankment stability, rather than the active-passive soil reactions against the sheet pile. The sheet piles were still in danger of sliding, even when the sheet-pile structural stability were already calculated as satisfactory.

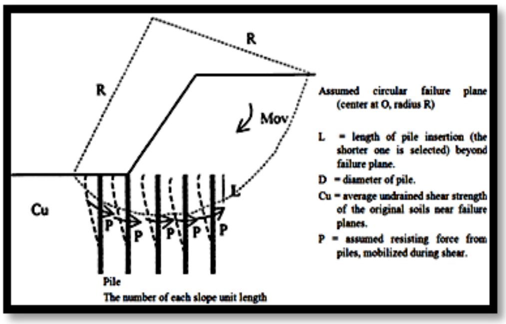
A laboratory study using model piles were conducted on soft soils (Rusdiansyah et. al., 2015) to investigate the increase of shear strength of the soft soils due to the existence of group of piles in the soils. The group of piles will add more resistance against lateral sliding of the soft soils, so that the effects of many variations of the piles and the soils can be investigated and formulated. The variations involved in this study were: space distance between the piles, length of the pile embedment, diameter of the piles, number of piles used, relative stiffness of the piles, and the relative stiffness of the soils themselves.

2. REFERENCIAL STUDY

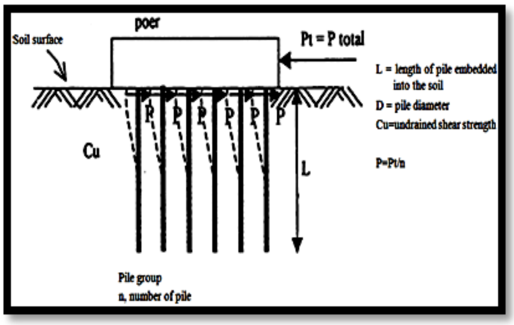
Theoretical background

Piles can be assumed to act as dowels when sliding occurs in the soil, so that the piles will produce additional resistance to the sliding plane to increase general stability of the soils against failure. Mochtar (2000) had developed a theory about the additional resistance to soil shear strength against sliding due to insertion of piles into the soils. This theory was based on the theory of piles against lateral force given in NAVFAC DM-7 (1971).

In this theory, the lateral resistance capacity of a pile in soil are governed by: stiffness and flexural moment resistance of the pile, length of pile penetration into the soil, shear resistance of the soil, and the number of piles per length of slope. The assumptions by Mochtar (2000) as given in Figure 2.a. is comparable with the assumption of group of piles against lateral force by NAFVAC DM-7 (1971) given in Figure 2.b.



(a)



(b)

Figure 2. Assumption used by Mochtar (2000) to find resistance of piles against lateral sliding;

(a). Actual piles to act as dowel resistance against lateral sliding under embankment or on slopes. Resisting forces P are working along the failure plane.

(b). Original assumption given by NAFVAC DM-7 (1971)

In his theory, Mochtar (2000) proposed the formula to obtain the number of piles needed to improve Safety Factor against sliding, and it was based on the ability of 1 (one) pile to resist against lateral force P. This pile resisting capacity against lateral force was also a function of the pile moment flexural resistance, Mp, pile coefficient Fm, and relative stiffness T, as follows:

$P_{max\ (analytical)\ of\ 1\ pile}$ = Maximum Lateral Resisting Force of 1 pile
= **($Mp_{max\ 1\ pile}$)/(Fm x T)** ……………............... (1)

in which:

$Mp_{max\ 1\ pile}$ = maximum flexural moment the pile can withstand;
Fm = coefficient of moment due to lateral load P (from NAFVAC DM-7);
$P_{max\ (analytical)}$ = maximum lateral load the (individual) pile can mobilized;

T =$[(EI_{\ of\ piles})/(f_{\ of\ soil})]^{0.2}$
= relative stiffness factor of piles compared to the soil strength (as given in NAFVAC DM-7, 1971).

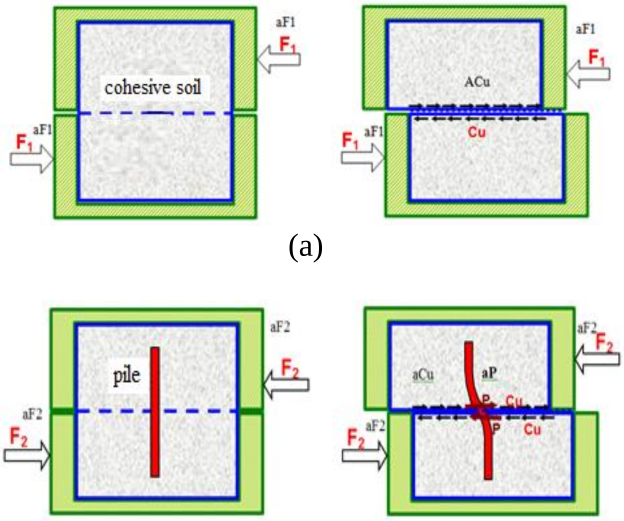
The above Equation (1) was further developed by Arya and Mochtar (2002) to include also the correction factors involving different variety of soils (Cu), different depth of soil penetrations (L/D), different diameters of piles (D), and different numbers of piles. This study was obtained from laboratory modeling using very small samples with diameter of wooden piles used about 1.0 to 2.0 mm, and the result was given in Equation (2) as follow:

$P_{max\ (analytical)\ of\ 1\ pile}$ = ***Fk*** **x ($M_{pmax\ 1\ pile}$)/(Fm xT)** ……………………….(2),

in which:

$$Fk = 2,643.\left[\frac{0,89 + 0,12L/D}{2,69}\right]\left[\frac{0,855Cu^{-0,392}}{2,865}\right]$$

The laboratory modeling and testing were conducted using the principles of Direct Shear test as shown in Figure 3. With the insertions of model piles in the soil samples, the increase of soil resistant against shearing forces could be measured.



(a)

(b)

Figure 3. Assumption used for the increase of soil resistance due to insertion of model pile (Mochtar, 2000; Arya and Mochtar, 2002)
(a). Condition without insertion of model pile.
(b). Condition with model pile inserted.

From Figure 3 (a), condition without model pile in cohesive soil ($\phi \approx 0$), when sheared to failure ; soil undrained shear strength= Cu;
F1 = Cu x A ; A = area of soil being sheared

Soil shear strength, $\tau = Cu + \sigma n \tan \phi$
$\rightarrow \tau = Cu$

From Figure 3(b), condition when model pile was inserted, the piles were acting as a dowel.
When sheared to failure ; F2 =(Cu x A) + P ;
P = assumed maximum resisting force from 1 (one) model pile.
If **n** number of model piles were inserted, F2 = (Cu x A) + (n x P).

The study in laboratory using model piles by Arya and Mochtar (2002) was still considered inadequate, since relatively very small samples were involved. Some other parameters were thought to be significantly important but not yet investigated, such as pile distances, pile arrangement, and pile inclination. Besides, it was much more difficult to make more homogenous model piles in their stiffness properties when using smaller model piles. Stiffness properties of relatively very small model piles were found to vary considerably from one pile to another. Therefore, further studies using bigger model and more homogenous model pile stiffness and involving as many as possible important parameters are still required.

Parameters influencing the improvement of Safety Factors of natural slopes reinforced with piles as resistance against lateral movement.

Literature studies conducted on the reinforcement mechanism of piles inserted into soils had concluded that the factors influencing the interactions were (Ashour and Ardalan, 2012; Ausilio, et. al., 2001; Frank and Puget, 2008; Kourkoulis, et. al. 2011, 2012, Mochtar, 2011; and Yang, et.al., 2011).

1. Length of the pile insertion beyond the failure plane,
2. Diameter and the relative stiffness of the model piles,
3. Relative strength of the soil surrounding the failure planes.
4. Position and configuration of pile within group of piles.
5. Number of piles resisting the lateral force.
6. Space distance between the piles.
7. Inclination of pile against direction of failure plane.

More recent investigators were mostly conducted their studies using numerical simulations. For example, a study by Ashour and Ardalan (2012) with the help of PCSLOPE revealed that the piles should be driven into the more stable soil layers beneath the shear plane to obtain better lateral resistant. Diameters of piles were also found to be significant in influencing the stability of soil against sliding. However, at smaller L/D ratio, larger diameters of model piles were found to cause reduction of safety factor against sliding. This study also concluded that location of piles nearer to the center of the failure plane would give maximum safety factor increase, while larger space distance between piles would cause reduction in safety factor against sliding, instead.

Kourkoulis, et. al. (2011) had performed their study using finite element modeling and the use of XTRACT software. The piles were inserted into assumed soils medium ranged form silty sand to soft rock. Kourkoulis, et. al. (2011) concluded that the longer pile insertion and the firmer types of soils were very important for the increase of shearing strength of the pile-soil interaction, while shorter space distance between piles would increase the resisting force, lower the moment working on the pile, and reduce the pile top deformation.

3. RESEARCH APPLICATION

Material Used

The soil used for this research was the typical clay soils found around the campus of ITS (the Surabaya Institute of Technology, in Surabaya, Indonesia), which had consistencies ranging from very soft to medium soils. The physical and mechanical characteristics of the soil can be given as in Table 1. This soil according to the USCS was classified as CH soil (high plasticity caly soil) and according to the AASHTO the soil was classified as A-7 (clay soil).

The mini piles used in this study were made of Meranti wood (wood of Class II in strength). The model piles were cylindrical inform with diameter 3 mm, 4.5 mm, and 6 mm, while the length of the pile was made according to the need of this research. The wood was specially selected to have mostly homogenous properties and water content in the wood were averagely about 14.87% and with average unit weight of wood was about 0.55 gr/cm3. From tensile stress tests performed on the mini wooden piles, the modulus of elasticity was found to have an average value of E = 21812.39 kg/cm^2, which is typical for wooden pile. The maximum tensile strength of the wooden piles was averagely of $\sigma_{tensile}$ = 780.518 kg/cm^2.

Table.1 Physical and mechanical characteristics of the undisturbed soil used the model soil-pile interaction.

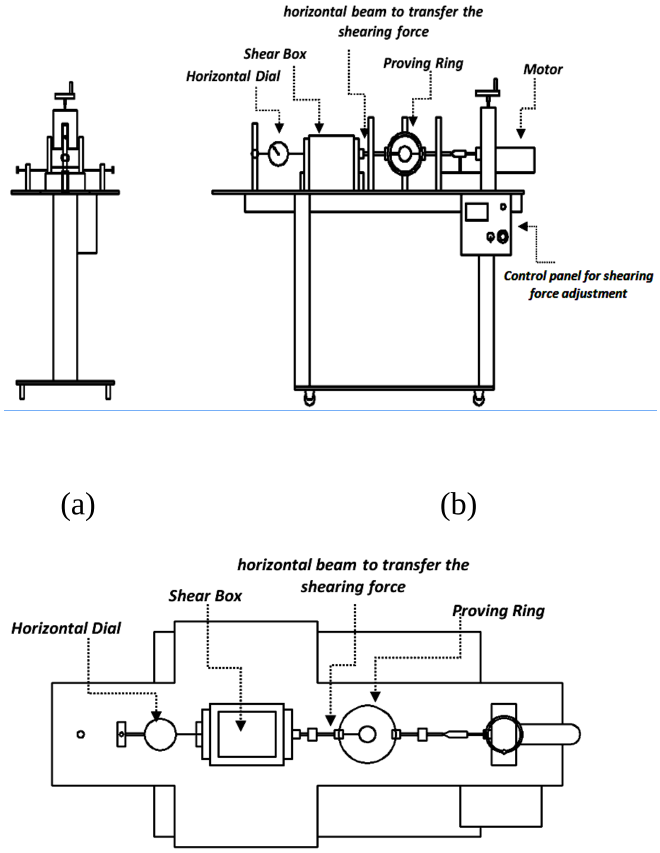
No.	Parameters(*)	Values
1	Unit weight, γt	1,424 gr/cm3
2	Water content, Wc	92,21%
3	Void ratio, e	2,567
4	Degree of saturatio Sr	100%
5	Specific Gravity, Gs	2,643
6	Liquid Limit, LL	64,90%
7	Plastic Limit, PL	30,33%
8	Plasticity Index, PI	34,57%
9	Percent Clay fraction	75,44%
10	Percent of Silt fraction	17,32%
11	Percent of Sand fraction	7,24%
12	Undrained, Cohesion, Cu	0,190 kg/cm2

(*) *Note : the depth of soil sample and depth of water table was in -1,2m*

Equipment.

The equipment used for testing was a modification of a Direct Shear test, in which the shearing box was modified to become larger to be able to contain the whole testing apparatus of model piles and soils. However, no loading and dial gage were needed in vertical direction, because shear loading was performed in horizontal direction only.

In the following Figure 4, the shearing apparatus is shown. The main components of this shearing apparatus are: (one) proving-ring with capacity to 500 kgf., horizontal beam to apply the shearing force, (one) dial gage to be able to measure up to 50 mm horizontal translation, one unit of motor to apply the horizontal force required, and two large shearing boxes with the sizes of 20 cm x 15 cm x 12 cm and 20 cm x 15 cm x 18 cm, in which the model piles and soils were assembled.



(a) (b)

(c)

Figure 4. Apparatus for shearing test (modification of the Direct Shear test)
(a) side view,
(b) frontal view,
(c) seen from above.

Testing Procedures

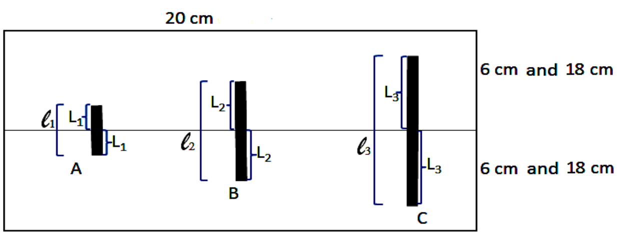
The undisturbed soils were taken directly from the field using special soil sampler, which had a form similar with the shearing box. The soils were then extruded from the sampler and then set up inside the shearing box, to become the model soils. On each model soil, the model piles were inserted using hand and using a special frame apparatus to help in assuring the position and the verticality of the model piles.

The motor had to be switched on to move the horizontal beam to shear the apparatus with a relatively constant shearing speed. The speed can be adjusted between 0.1 mm/minute to 2 mm/minute. The amount of force applied on the horizontal beam was equal to the total shearing force, and these forces were measured by means of reading the proving ring. The horizontal force in this measurement were designated as P_{lab} and they were recorded simultaneously with the horizontal displacement of the shearing box.

During testing the model soils and piles, the following variables were attempted, which were:

1. Variations of L/D ratio, (depth of pile insertion, L, to pile diameter, D) in which L/D = 5, 10, and 15.
2. Variations of space between model piles, S; in which S = 3D, 5D, and 8D.
3. Variations of model pile diameters, D; in which D =
   0.3 cm, 0.45 cm. and 0.6 cm.
4. Variations in directions of pile queuing and number of piles, which were:
   - 2 piles, either 1 x 2 or 2 x 1, depending on the direction of shear; 1 x 2 means the 2 piles were in one line in the direction of shear, while 2 x 1 means the 2 pile were in line perpendicular to the direction of shear.
   - 3 piles, either 1 x 3, or 3 x 1.
   - 4 piles : 1 x 4, 4 x 1, or 2 x 2.
   - 6 piles : 1 x 6, 6 x 1, 2 x 3, or 3 x 2.

More complete explanation can be given in Figure 5 to 7



A = L_1/D =10   B = L_2/D =15   C = L_3/D =20

- For D = 0,3 cm	then	L_3/D = 20	L_3 = 6 cm	l_3 = 12 cm
		L_2/D = 15	L_2 = 4,5 cm	l_2 = 9 cm
		L_1/D = 10	L_1 = 3 cm	l_1 = 6 cm
- For D = 0,45 cm	then	L_3/D = 20	L_3 = 9 cm	l_3 = 18 cm
		L_2/D = 15	L_2 = 6,75 cm	l_2 = 13,5 cm
		L_1/D = 10	L_1 = 4,5 cm	l_1 = 9 cm
- For D = 0,6 cm	then	L_3/D = 20	L_3 = 12 cm	l_3 = 24 cm
		L_2/D = 15	L_2 = 9 cm	l_2 = 18 cm
		L_1/D = 10	L_1 = 6 cm	l_1 = 12 cm

Figure 5. Illustration for the variations of the length of pile insertion.

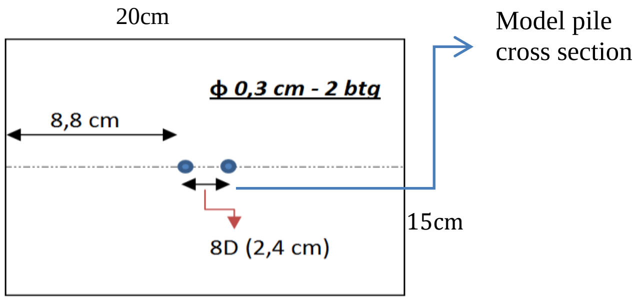


Figure 6. Illustrated example of the position of 2 model piles with spacing between piles = 8D (seen from above)

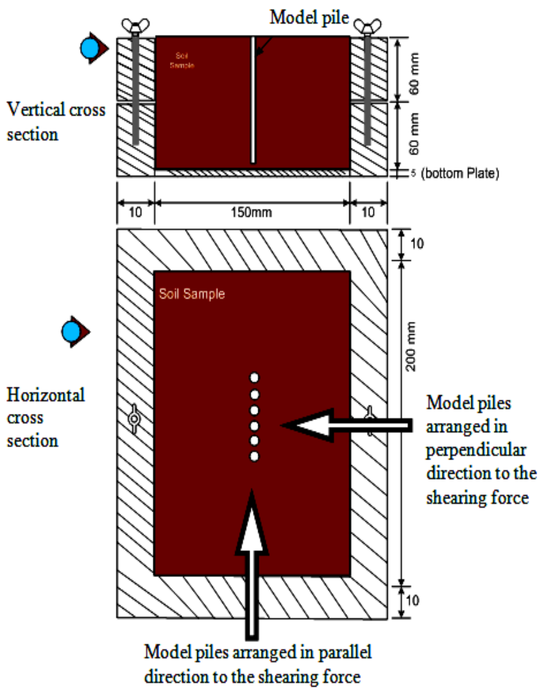


Figure 7. Illustrated position of model soils and piles inside the shear box relative to the direction of shearing

4. RESULTS AND DISCUSSION

4.1. The influence of the ratio of pile insertion, L/D, to the increase of shearing resistance.

In Figure 8, the curve showing the relationships among various ratios of pile insertions L/D (i.e. L/D = 5, 10, 15, and 20; in which D is pile diameter) with the increase of shearing resistance of the model pile-soil interaction. The shearing resistance of pile were represented by the ratios of $P_{lab}/P_{analitical}$. In this tests, the value of P_{lab} represented the lateral resistance obtained from measuring the resistance of one model pile in this laboratory study with the same soil sample, while $P_{analitical}$ represented the calculated lateral resistance of one model pile when using the formula given by Mochtar (2000) in Equation 1, for the given model pile. The ratios of pile spacing, S, were also varied for S = 3D, S = 5D, and S = 8D. It was apparent that all the correlations tended to be linear, in which the space ratio S = 5D (or S/D = 5) was found to give the highest results, while the ratio S=8D (or S/D = 8) was to yield the lowest results.

If from all the results in Figure 8, one could recalculate again the ratio of any P_{lab} with the measured P_{lab} at insertion ratio L/D = 15, from the same pile spacing ratio S/D; and all the results of $(P_{lab\ for\ L/D \neq 15})/(P_{lab\ at\ L/D\ =\ 15})$ can be plotted against the pile insertion ratio. The result could be simply represented by one linear line as given in in Figure 9. This linear value was found to be nearly accurate enough to describe the correlation, since the value of chi-square of regression, R^2, was about 0.930. This correlation meant that the lateral shearing strength of piles would increase with the increase of the depth of pile insertion.

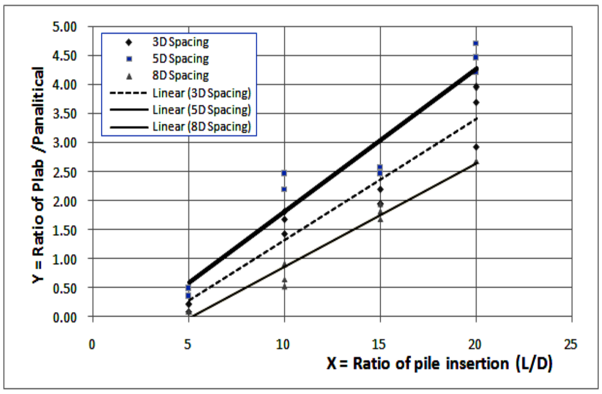


Figure 8. The relationship between pile insertion ratios with $P_{lab}/P_{analitical}$ for various spacing between model piles S = 3D, S = 5D, and S = 8D.

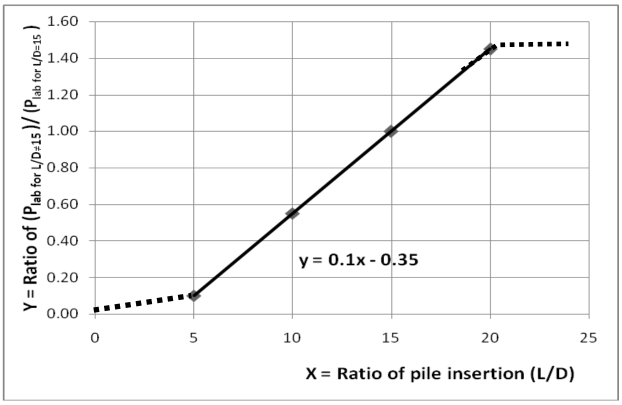


Figure 9. The correlation between various ratio of $(P_{lab\ for\ L/D \neq 15})/(P_{lab\ at\ L/D\ =\ 15})$ with the pile insertion ratio L/D. (In here $P_{lab\ at\ L/D\ =\ 15}$ is the pivoting point and is assumed = 1.0)

It should be pointed out here that when L/D < 5, the equation follows the dotted line Y = 0.02 X, while the maximum value of Y should be ≤ 1.45.

4.2. The influence of the ratio of pile spacing, S/D, to the change of shearing resistance.

The results of testing with different ratios of pile spacing, S/D, was given in Figure 10, in which the results of $P_{lab}/P_{analitical}$ were plotted against the pile spacing ratio S/D. In this tests, the value of P_{lab} represented the lateral resistance obtained from measuring the resistance of one model pile in this laboratory study with the same soil sample, while $P_{analitical}$ represented the calculated lateral resistance of one model pile when using the formula given by Mochtar(2000) in Equation 1 for the given model pile.

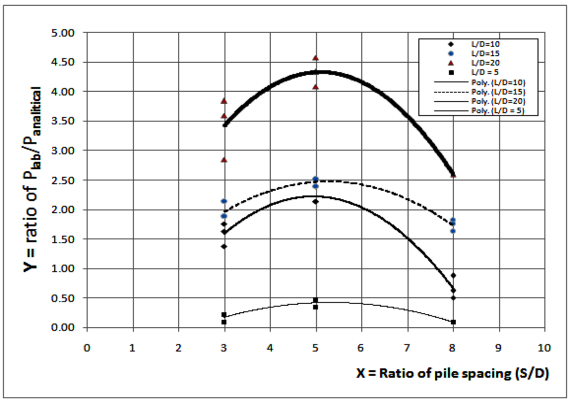


Figure 10. The curves showing correlations between ratios of pile spacing S/D with ratios of $P_{lab}/P_{analitical}$ for different pile insertions, L/D.

Similarly with the previous method, the results in Figure 10 can all be recalculated back using the value of P_{lab} at S/D =5 as the pivoting value for every family of result with the same L/D ratio. Therefore, if the values were recalculated so that $(P_{lab\ for\ S/D \neq 5})/(P_{lab\ for\ S/D = 5})$ obtained from the same L/D ratio were all plotted against the spacing ratio S/D, the results showed very good correlation in quadratic polynomial in Figure 11, in which the chi-square regression value ,R^2, was 0.725. The result in Figure 11 showed that the pile spacing were rather significantly influencing the amount of pile resistance against lateral sliding, while the pile spacing s/D = 5 yielded the highest result.

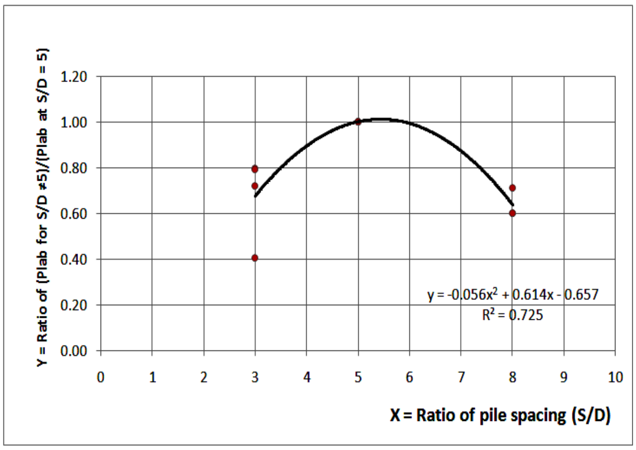


Figure 11. Correlation between ratios of $(P_{lab\ for\ S/D \neq 5})/(P_{lab\ for\ S/D = 5})$ for various ratios of pile spacing, S/D. (In here $P_{lab\ at\ S/D = 5}$ is the pivoting point and is assumed = 1.0)

4.3. The influence of the number of piles in a row to the increase of shearing resistance.

It was observed from this laboratory study that the number of pile in row also significantly influenced the lateral resistance of the model pile, but not directly in proportion with the pile quantity. In Figure 12, the ratio of Y (= $P_{lab}/P_{analitical}$) was plotted against X (=the number of piles in a row). The correlation were practically linear. However, if the value of any P_{lab} was then compared with the value of $P_{lab\ at\ X=1}$ the resulting correlation was also linear, but with slight decrease in lateral resistance. The correlation was given in Figure 13. The latter correlation was by assuming the value of P_{lab} =1 when the number of pile ,X, was merely one. Therefore, when the number of piles $\neq$ 1, the obtained ratios of ($P_{lab\ at\ X=1}$ /$P_{lab\ at\ X \neq 1}$) could be plotted. The correlation obtained from Figure 13 was very well represented by a straight line with a Chi-square, R^2, value of 0.986. The result in Figure 13 showed that the use of more piles as resistance against sliding would decrease the lateral capacity of each individual pile, similar to that of efficiency factor used in group of piles under axial loading.

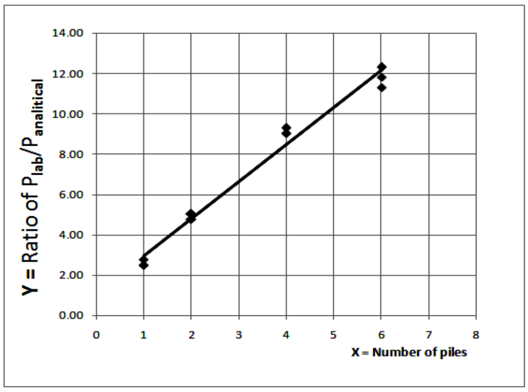


Figure 12. Correlations between ratio Y =$P_{lab}/P_{analitical}$ against the number of piles in a row

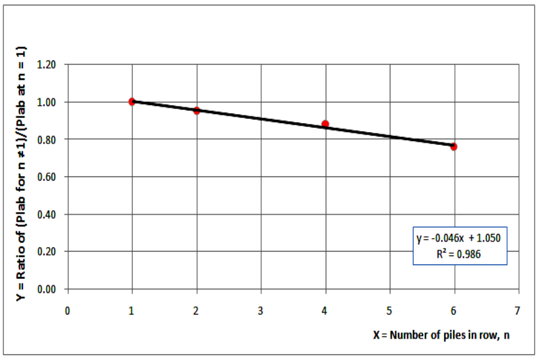


Figure 13. Correlation between ratio of $P_{lab\ at\ x\neq1}$/ $P_{lab\ at\ x=1}$ and number of piles in a row (=X). (In here $P_{lab\ at\ x=1}$ is the pivoting point and is assumed = 1.0)

4.4. The influence of the pile diameter to the increase of shearing resistance.

In Figure 14, the ratios of pile diameter D/T were plotted against the ratios of P_{lab} for diameter of In this case the values of $P_{lab\ at\ D=3mm}$ was used as the pivoting point and was assumed = 1.0 when D = 3mm pile 3 mm and other diameters (4.5 mm and 6.0 mm).

The correlation between the ratios ($P_{lab\ at\ D\neq3mm}$/$P_{lab\ at\ D=3\ mm}$) and the ratios of D/T was found to be best fitted by a straight line. The value of T represented the relative stiffness factor of piles compared to the soil strength (as given in NAFVAC DM-7, 1971), which is:

$$T = [(EI_{\text{of piles}})/(f_{\text{of soil}})]^{0.2}$$

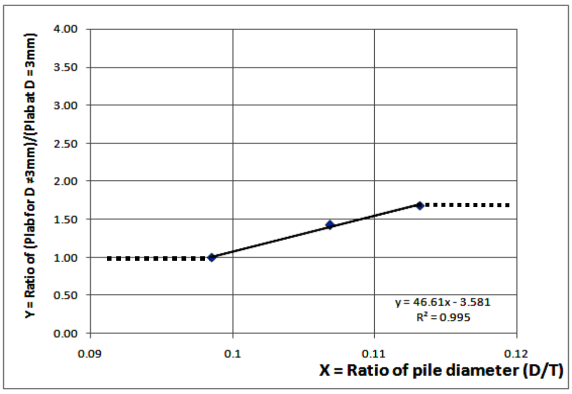


Figure 14. Correlation between ratio of pile diameter D/T and ratio of P_{lab}

It was apparent from Figure 14 that the increase in pile diameter would have also caused the increase of shearing resistance of the pile-soil interaction model. It should be noted however, this correlation value should be used within the given range of the D/T values. Should the D/T value is larger than that given in Figure 14 (D/T = 0.146), the maximum number of Y Ratio given in Figure 14 (Y = 1.70) be used, instead. Likewise, if the D/T ratio is smaller than 0.126, the minimum number Y = 1.0 should be used.

4.5. The influence of pile inclination against direction of failure plane.

Different pile inclinations were tried in this laboratory study of pile-soil interaction model. The results showed that all other pile inclinations against the directions of the failure plane, other than 0˚ angle, would result higher resistance than the standard value of testing at 0˚ angle. In here, angle of inclination 0˚ meant the model pile was perpendicular with the failure plane, or the model pile made 0˚ angle with the line normal to the failure plane. Furthermore, considering the difficulty in determining the actual angle of pile inclination in the field (in reality), while most of the piles insertion can be assumed to have 0˚ angle with the failure plane, the results of pile inclination of other angles than 0˚ was not investigated further. By assuming all the piles to be in the right angle with the failure plane, the assumed result will give a lower resistance values (therefore, result better safety factor) than the actual pile resistance in the field.

4.6. Suggested Formula for the Increase of Lateral Soil Resistance due to the Insertion of Pile in Ground.

The formula for the increase of soil resistance due to the insertion of pile into the ground, that was previously given by Mochtar (2000), could then be modified to include the results from regression analysis mentioned in the proceeding sections. The new formula would also include the parameters such as: pile insertion ratio, pile spacing ratio, number of pile in a row, and pile diameter ratio. The results can be summarized in Table 2.

Tabel 2. Formula for Increase of Lateral Resistance of Model Pile Inserted into Soft Soil

Variable of model pile-soil interaction	obtained average of P_{lab} / $P_{analitical}$	Regression Formula obtained from Section 4
Ratio of Pile Insertion, Xt = L/D	1.965	**$Y_t = 0.1(X_t) - 0.35$;** (Yt = 1.0 when L/D = 15) (For 0 < L/D < 5, Yt = 0.02 Xt) ($Y_{t\ max}$ = 1.45)
	2.467	
	1.756	
Ratio of Pile Spacing, Xs = S/D	0.422	**$Y_s = -0.057(X_s)^2 + 0.614(X_s) - 0.658$;** (Ys = 1.0 when S/D = 5)
	2.216	
	2.467	
	4.336	
Number of Piles in Row = Xn	2.590	**$Y_n = -0.047x_n + 1.051$;** (Yn = 1.0 when Xn = 1)
Ratio of Pile Diameter, X_D = D/T	2.467	**$Y_D = 46.616(X_D) - 3.582$;** ($Y_D$ = 1.0 when D/T = 0.1) ($Y_{D\ min}$ = 1.0 ; $Y_{D\ max}$ = 1.70)
Average	**2.30**	

Note : $P_{analitical}$ was calculated from Equation 1.

The formula of lateral resistance borne by a pile inserted into the soft ground will be:

$P_{max\ (analytical)\ of\ 1\ pile} = F_k \times (M_{pmax\ 1\ pile})/(F_m \times T)$ ……………………………………………..(3)

In which Fk = 2,30 x Yt x Ys x Yn x Y_D ; and the equations of Yt, Ys, Yn, and Y_D are those given in Table 2, and:

$P_{max(1pile)}$ = maximum lateral force can be mobilized by 1pile
F_k = combined correction factor.
M_{pmax} = maximum flexural moment of each pile (kg-cm).
fm = moment coefficient for lateral force P(from chart on NAVFAC DM-1971)
T = Relative stiffness factor, cm = $[(EI_{\ of\ piles})/f_{\ of\ soil}]^{0.2}$
D = diameter of pile, cm
E = Young's modulus of elasticity of pile, kg/cm2
I = moment inertia of pile (against flexural bending) , cm4
F = coefficient of variation of soil modulus , kg/cm3 (from chart on NAVFAC DM-1971).

In Figure 15, the procedure to calculate the number of piles needed for soil reinforcement in the field is given. (n = designed number of pile in row, R = radius of the circular failure plane, SF = Safety Factor of the slope against failure)

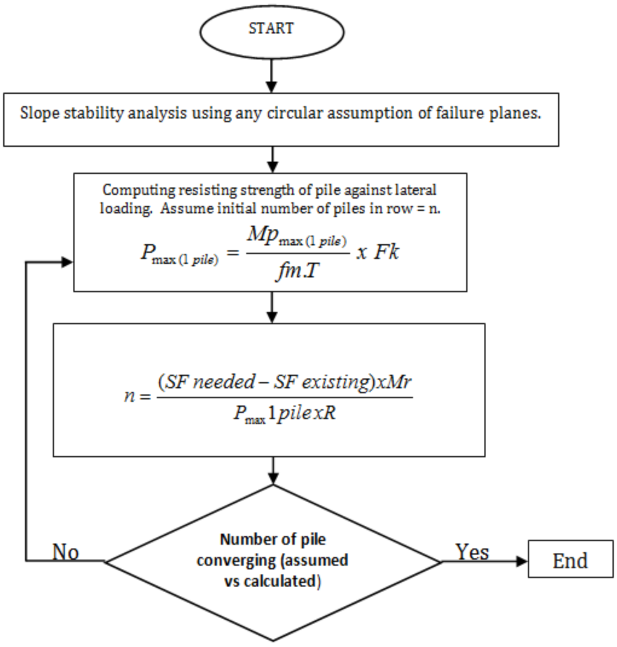


Figure 15. Procedure of designing the number of piles in row

5. CONCLUSION

The conclusion of this study can be given as follows:

1. The formula for estimating lateral resistance of pile inserted into soft ground has been established. This lateral resistance will significantly increase the ability of the soil against lateral movement, which is initially only resisted by the shearing strength of the soil alone.
2. The lateral resistance of pile will be influenced mainly by the ratio of pile insertion, the ratio of spacing between piles – with the ratio S/D = 5 is the most

effective for pile spacing, number of piles in row, and the ratio of pile diameter.

3. The combined influences can be reflected into a Factor ,F_k, which is used to modify the Equation 3 in this study.

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