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Improving the Bearing Capacity of Marine Clay using Polyurethane Columns

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Abstract. Problematic soil such as marine clay causes structures or pavement to crack and collapse as marine clay possesses low bearing capacity. Therefore, ground improvement is usually conducted to improve the bearing capacity. Since the use of cement for strengthening weak soil is not environmental-friendly, the aim of this study is to improve the bearing capacity of marine clay using polyurethane (PU) columns. The properties of the marine clay collected from Batu Pahat determined were particle size distribution, Atterberg's limits, specific gravity, and compressibility were determined. A series of small-scale physical modelling was conducted with a tank's size of 500 mm x 500 mm x 200 mm. The 1:1 ratio of poly and isocyanate was injected into the cored hole for the column formation with the area improvement ratio was set as 12.6%. The loading process was conducted 1 day after column installation. Double tangent method from the stress-displacement curve was employed to determine the ultimate bearing capacity of the marine clay. The ultimate bearing capacity of the untreated marine clay was 50 kPa. In addition, the results showed that the ultimate bearing capacity of the marine clay increased with the length of the PU columns. A maximum improvement ratio of 220% was achieved for the end bearing PU columns. Comparing the improvement ratio with the published data showed that PU columns had a better performance than soil cement or deep mixing cement columns due to its lightweight and high strength. Therefore, the replacement of cement with PU is workable and sustainable in ground improvement method.

1. Introduction

These days, rapid development has caused high usage of land in Malaysia. However, unexpected condition such as problematic soil causes problem for the construction. Low bearing capacity and large settlement are among the features of problematic soil such as marine clay. Marine clay with low bearing capacity and large settlement will inevitably cause problem during and after construction This is due to the fact that the soil is unable to withstand the load from the superstructures and causes it to fail. As a result, the structure will lean, collapse, and eventually being demolished due to foundation failure. Besides structure failure, large magnitude of settlement lead to pavement failure, uneven surface of the pavement and pavement cracking [1]. Hence, the effect of problematic soil is widely adverse and cannot be ignored. However, the developed ground improvement methods may not sustainable (i.e. cement) and usually costly (i.e. micropile). The use of soil cement column and deep soil mixing with cement are unsustainable due to high usage of cement. Furthermore, the application of traditional ground improvements method such as embankment and loading may take longer time to achieve the desired strength and settlement. Alternatively, PU is used as a pile to improve the ground condition and to achieve the desired bearing capacity. The use of PU apart from shortening the construction time, it is also more sustainable, non-toxic, cheaper progress and more favourable than the previous ground improvement methods. Thus, replacing cement with polyurethane columns is investigated in this paper to increase the bearing capacity of marine clay.

Marine clay, which usually exists in offshore areas has a high level of uncertainty in its properties and considered as a problematic soil [2]. The physical and geotechnical properties of marine clay is reviewed based on the published data from past researchers [3] [4]. In terms of particle size distribution, marine clay consists of high percentage of clay content which is above 55% except for marine clay from Pasir Gudang, Johor Bahru (26%) [5] and Kuala Muda (25.9%) [6]. Due to high clay content, the liquid limit (*LL*) and plastic limit (*PL*) of marine clay are high ranging from 36.8% to 95.8% and 20% to 47%, respectively. The pH values of marine clay vary from place to place as some are acid [3] [4] while some are alkaline [7] [8]. The loss of ignition (*LOI*) of marine clay is low, ranging from 4.25% to 8%. As a result, the geotechnical properties of marine clay are poor due to the poor physical properties mentioned above. For example, the shear strength of marine clay ranges from 10 to 75 kPa [3] [9] [10]. The permeability of marine clay is low, which ranges from 1.10 to 2.44×10^{-9} m/s due to high silt and clay content [6]. The compression index (C_c) of marine clay is 0.125 and it takes 588 days to achieve 90% of consolidation [11].

There are many methods for the PU production. The most common method is through the reaction between polyol and isocyanate group which contain not less than two isocyanate and hydroxyl functional groups [$R\text{-}(N{=}C{=}O)_n \geqslant 2$] and [$R1\text{-}(OH)_n \geqslant 2$], respectively [12]. The role of polyol and isocyanate in PU process are as expansion and bonding agent, respectively [7]. The mixing ratio of polyol and isocyanate is crucial for determining the strength of PU. A high percentage of polyol produces brittle PU while a high percentage of isocyanate produces higher strength of PU but smaller volume due to less expansion [13]. The ideal mixing ratio for PU production is 1:1 for providing adequate strength and expansion [7] [13]. PU is invented by Prof Dr Otto Bayer and modified for commercialisation [14]. PU is widely used in many industries such as construction, medical, automotive, packaging, marine and manufacturing due to low cost and high flexibility [15].

The reviewed ground improvement methods in this paper are grouting, stone column and micropile due to their similarity with PU columns. The aim of grouting is to improve the bearing capacity of soil and reduce the settlement. There are many types of grouting such as deep mixing method (DMM), injection grouting method (IGM) and jet grouting method (JGM) [15]. The materials for grouting are categorised into two, which are chemical and cementation grouts. Previous researchers proved that the use of chemical grout such as PU is a better choice than cementation grouts due to sustainability, low curing time, low labour work and better performance in reducing soil settlement and increasing soil bearing capacity [16]. Stone column is a ground improvement method via inclusion of high permeability, strength and stiffness gravel as column to accelerate the consolidation process and increase the soil bearing capacity. The effectiveness of stone columns is affected by the columns' lengths, arrangement and area replacement ratio. Longer columns' lengths, higher area replacement ratio and uniform distributed columns provide better performance in improving the Young's modulus of soil and indirectly reducing the soil settlement [17] [18]. Micropile is another ground improvement method to increase the soil bearing capacity and reduce settlement. Micropile raft (MPR) is invented from micropile for ground improvement and foundation system. MPR increases the soil bearing capacity and stiffness thus reduces soil settlement [19]. The effective pile length of mircopile is about three times the depth of failure area for punching shear failure to improve the bearing capacity of MPR [20].

Physical modelling tests conducted by researchers are reviewed. Three of them are using cement deep mixing (CDM) column as the improvement method [21] [22] [23]. All the physical modelling tests focused on soft soil such as peat and kaolin. The fabrication method of columns, geometrical set up of apparatus and specification of columns are reviewed for conducting the physical modelling using PU columns for this research. The results from the physical modelling tests prove that CDM columns improve the bearing capacity of soil.

2. Methodology

Basic testing was conducted before the physical modelling to determine the properties of the soil. Particle size distribution, Atterberg's limit, specific gravity and oedometer were the tests conducted to obtain the basic characteristic of the marine clay. All the tests conducted are based on BS 1377: 1990: Part 2 and Part 5. The model design, boundary condition, sample preparation, column installation, loading procedure and evaluation method were stated for conducting the physical modelling.

The size of PU columns was determined based on the size of CDM columns. The diameter, *D* varied from 0.5 m to 1.75 m and the length, *L* is usually varied from 10 m to 30 m [24]. Taking the *L*=12 m and *D*=1.5 m with the scale of 1/50, the diameter of the PU columns was decided to be 30 mm with length of 240 mm. The spacing between the PU columns are 2.5*D* to 3.5*D* based on BS8006: 1995. Thus, a spacing of 3*D* was used for this research. The boundary condition of the physical modelling was decided based on Prandtl failure mechanisms. Based on the Prandtl failure mechanism, the critical distance needed from the edge of the footing depends on the width of footing, *B* and soil friction [21]. Since marine clay is cohesive soil, the minimum distance from the edge of the footing is *B*. With this, the boundary condition was decided to be 1.167*B* which is larger than *B*. The depth of the tank was decided based on French Method [25]. According to French Method, the minimum depth of influence is 1.5*D* above and below the tip of pile. Therefore, the depth of influence was set as 1.67*D* which is larger than 1.5*D*. Overall, the tank size was decided to be 500 mm (length) x 500 mm (width) x 200 mm (height).

The marine clay was mixed with water equalled to 1.5 times of the liquid limit and consolidated using a steel plate with dimension of 498 mm x 498 mm x 10 mm. Figure 1 shows the mixing process of the marine clay with water. The pressure of the consolidation was increased to obtain homogenous marine clay with an undrained shear strength of 10 kPa [10]. The consolidation process took approximately 9 days to complete and the process is shown in Figure 2. After consolidation, vane shear test was conducted to check the undrained shear strength of the marine clay. After that, PU with ratio 1:1 was injected after the soil was cored out utilizing a steel pipe with an inner diameter of 30 mm. Figure 3 shows the equipment for PU injection. The minimum curing time for PU to achieve 90% of its strength is 15 minutes [26]. Thus, 24 hours curing were chosen for PU to fully react and harden. Figure 4 shows the PU column inside the marine clay after curing.

Five models named as model 1, 2, 3, 4 and 5 with different length of columns were prepared and loaded. Table 1 shows the specification of the model. The plan view of the tank is shown in Figure 5 while Figure 6 to 9 illustrate the cross-sectional view of model no. 2 to 5. Next, Figure 10 shows the geometry set up of the physical modelling. The loading process was conducted under constant rate of pressure. The settlement was measured using two linear variable differential transducers (LVDTs) of 100 mm capacity, placed on opposite sides across the centre of the rectangular footing. The ultimate bearing capacity of marine clay was determined using double tangent method from the stress-displacement curve.

Figure 1. Marine clay mixing process

Figure 2. Consolidation process of marine clay

Figure 3. PU injection equipment

Figure 4. PU column after curing

Table 1. Specification of model for physical testing

Model No.	Number of PU columns	Area improvement ratio (%)	Length of PU columns (mm)	Length ratio (%)
1	0	0	N/A	0
2	4	12.6	50	25
3	4	12.6	100	50
4	4	12.6	150	75
5	4	12.6	200	100

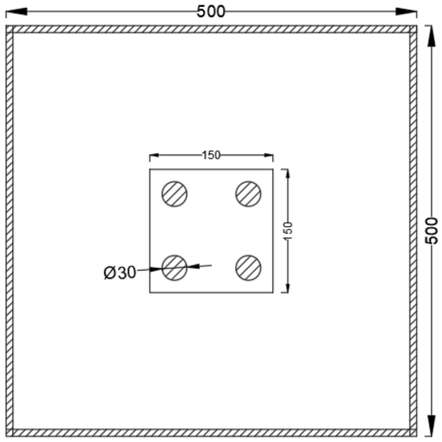

Figure 5. Plan view of tank model

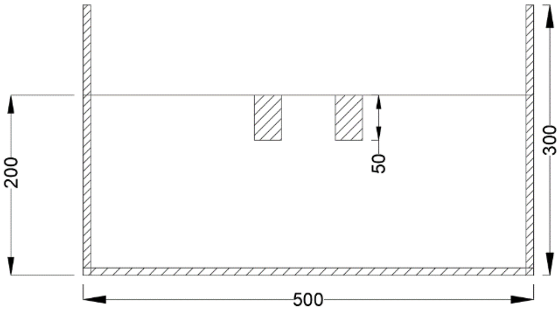

Figure 6. Cross sectional view of Model no. 2

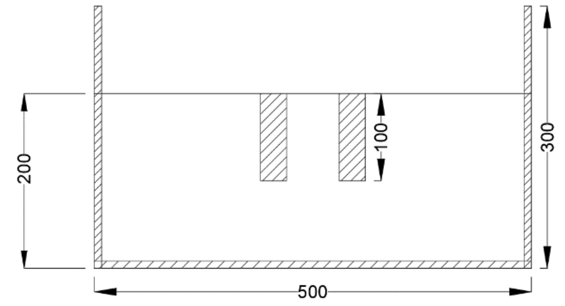

Figure 7. Cross sectional view of Model no. 3

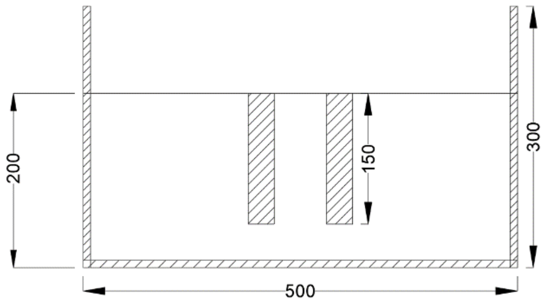

Figure 8. Cross sectional view of Model no. 4

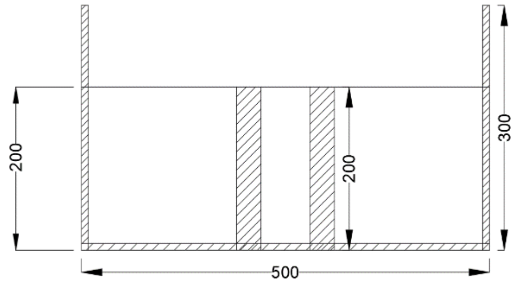

Figure 9. Cross sectional view of Model no. 5

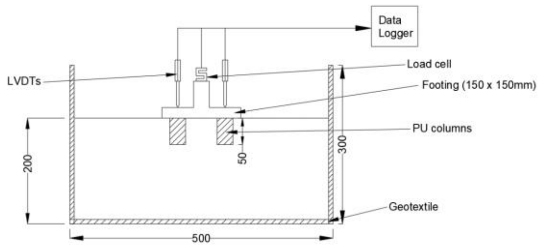

Figure 10. Geometry set up of marine clay

3. Results and Discussion

3.1 Physical properties of marine clay

Marine clay is classified as high plasticity clay (CH) based on British Soil Classification System (BSCS). The results of the particle size distribution and Atterberg's limits are tabulated in Table 2. The compressibility of marine clay was determined by conducting oedometer test on samples cored from the tank after the physical modelling test to obtain the compression and rebound index. The comparison is based on the same type of soil which is marine clay while the location is vary. Therefore, it is acceptable that there is difference between this study's results and the published data. However, most of the data are not far apart except the compressibility properties. The difference may due to the method of sample preparation was different.

Table 2. Comparison for basic testing result of marine clay

Name of test		This study	Published Data	Sources	Location
Particle size distribution (Laser scattering analyzer-LV-960V2)	Sand	1.5%	1.32%	[3]	Batu Pahat, Johor
	Silt	86%	98.68%	[3]	Batu Pahat, Johor
	Clay	12.5%			
Atterberg's limit	Liquid limit	55%	65%	[27]	Nusajaya, Gelang Patah, Johor
	Plastic limit	25%	26%	[3]	Batu Pahat, Johor
	Shrinkage limit	12%	17%	[28]	Sabak Bernam, Selangor
Specific gravity		2.55	2.62	[27]	Nusajaya, Gelang Patah, Johor
Compressibility index	Compression index	0.375	0.614	[28]	Sabak Bernam, Selangor
	Rebound index	0.064	0.169	[28]	Sabak Bernam, Selangor

3.2 Physical modelling results

The experimental results were analysed and compared with previous similar research such as [21] [22]. The ultimate bearing capacity of marine clay was determined using double tangent method from stress-displacement curve. Table 3 and Figure 11 shows the result for the physical modelling. Based on the results, the undrained shear strength determined by vane shear test for each model was less than 10 kPa. The results indicate that the ultimate bearing capacity of marine clay increased with the length of PU columns because the skin resistance between the PU columns and soil increases. The maximum improvement ratio achieved was 220% for end bearing PU columns. This is because, end bearing PU columns possess both tip resistance and skin resistance. However, tip resistance is much higher than skin resistance. Therefore, the effect of skin resistance is negligible. Besides, based on Figure 11, the stress displacement curve of model number 5 (end bearing PU columns) behaved abnormal after 20% of strain due to the shortening of PU columns. For model number 1 (untreated marine clay), the abnormal behaviour started early which was before 20% strain. It is believed that the abnormal behaviour was due to the incomplete consolidation process, resulting some void was left over between the soil particles.

The result was compared with the published data [21], [22]. The comparison results are show in Table 4 and Figure 12 The type of soil and material of columns used by this study are different from the previous research. This study’s result shows a better improvement ratio when compared to the published data. This is due to the light weight and high strength of PU. Thus, PU is a better material to replace cement due to its high strength, better performance and more sustainable to be used in ground improvement [29].

Table 3. Experimental result for 5 physical models

Model Number	Column Length (mm)	Undrained shear strength of soil (kPa)	Ultimate bearing capacity (kPa)	Improvement ratio (%)
1	N/A	6	50	0
2	50	8	58	16
3	100	9	130	160
4	150	8	140	180
5	200	8	160	220

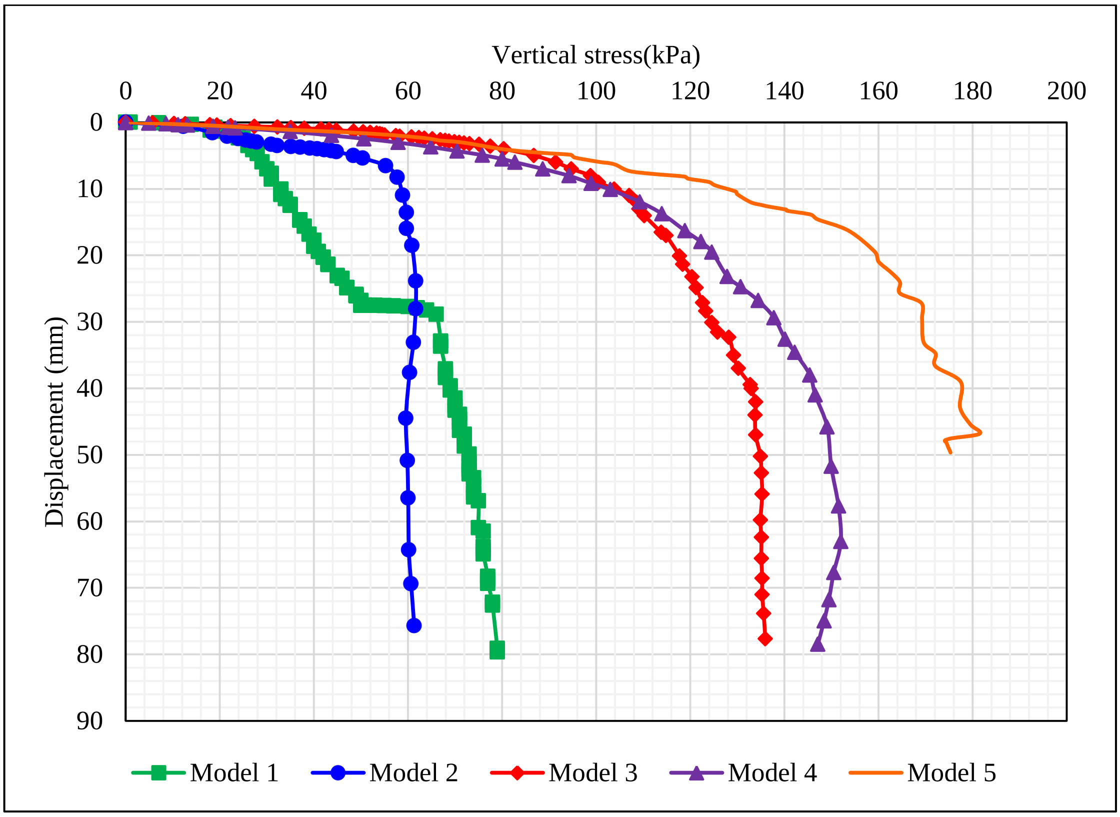

Figure 11. Stress displacement curve for 5 physical models

Table 4. Comparison result of this study's result and published data

Sources	**This study**	[21]	[22]
Type of soil	Marine clay	Peat	Kaolin clay
Ground Improvement method	PU columns	Deep mixing cement columns	Soil cement columns
Area Improvement ratio (%)	12.6	13.1	26
Length ratio (%)	**Improvement ratio (%)**		
0	0	0	0
25	16	40	N/A
50	160	62	99
75	180	65	N/A
100	220	104	191

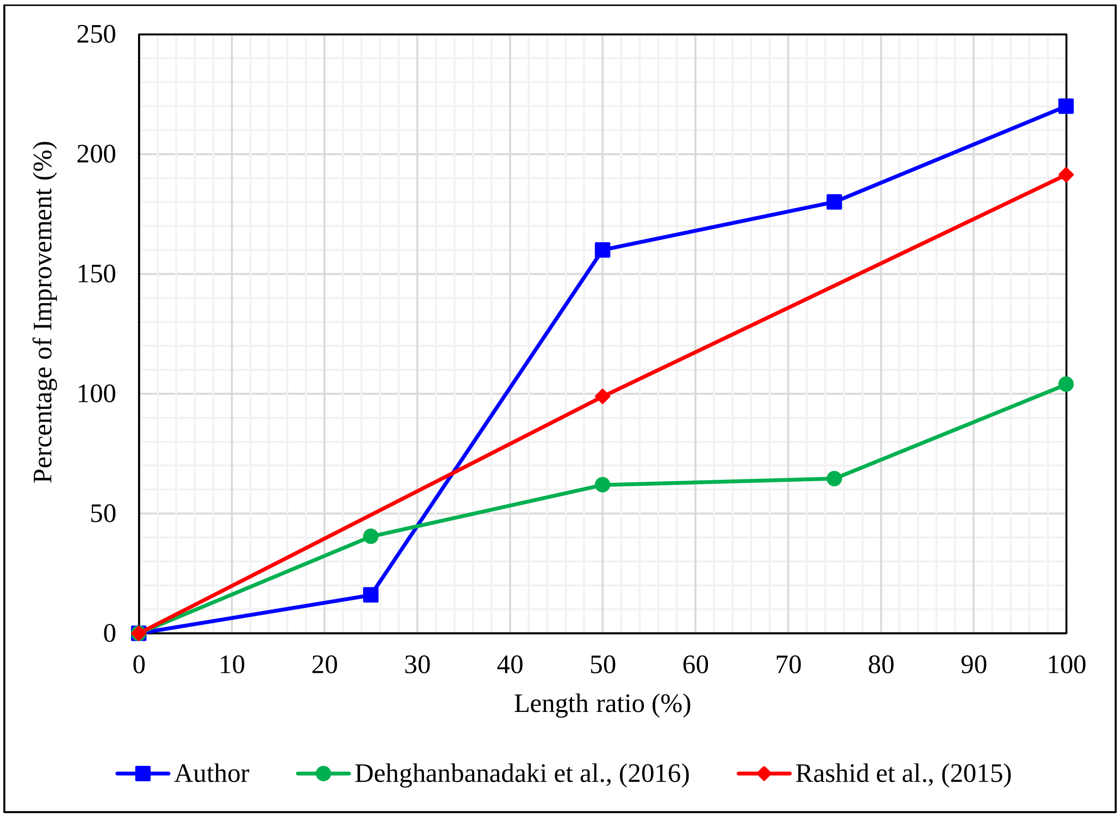

Figure 12. Relationship between length ratio and improvement ratio from this study's result and published data

4. Conclusions

Basic test and physical modelling test were conducted successfully. The conclusions that can be drawn from the study are as follows:

a) The basic testing result showed that the soil is high plasticity clay (CH) based on the classification of BSCS. The soil possesses 55% liquid limit, 25% plastic limit and 12% shrinkage limit. The specific gravity of the soil is 2.55. The compression index and rebound index are 0.375 and 0.064, respectively.
b) The ultimate bearing capacity of the untreated marine clay is 50 kPa.
c) The ultimate bearing capacity of the treated marine clay with 50, 100, 150, and 200 mm length of polyurethane columns are 58, 130, 140, and 160 kPa, respectively. The area improvement ratio is kept constant as 12.6%. The length of the polyurethane columns increased the ultimate bearing capacity of the marine clay. The ultimate bearing capacity of marine clay improved from 50 kPa to 160 kPa with an improvement ratio of 220%.

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