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Static Response on Lime Column and Geotextile Encapsulated Lime Column (GELC) Stabilised Marine Clay under Vertical Load

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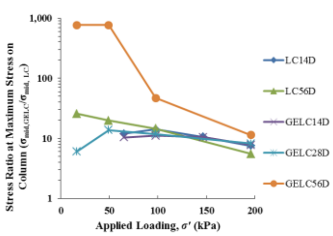
Graphical abstract



Abstract

Marine clay, which is widely encountered in coastal area in Malaysia, is a problematic base material. Previous researchers reported that deep lime stabilisation can significantly improve clay. However, insufficient confining pressure from surrounding soil normally lead to the inferior performance on the upper part of column such as column head crushing and larger deformation on the surrounding soil at top part of column. Therefore, geotextile encapsulation was proposed for lime column in this study. Static response and stress distribution are essential in the understanding on behaviour of columnar stabilised soil under vertical load. Multi stages loading tests were conducted on Pontian marine clay, with and without geotextile encapsulation. Stress concentration ratio (σ_{mid}/ σ_{soil}) was examined in each loading stage, where it is defined as stress on column (σ_{mid}) divided by stress on surrounding soil (σ_{soil}). The samples were cured for 14, 28 and 56 days before tested. It was found that stress concentration ratio was dependent on column materials strength properties and applied loading. Geotextile encapsulation increased the stress concentration ratio on lime column. Stress concentration increment effect by geotextile encapsulation was further enhanced by the confining pressure of surrounding soil; however, the effect reduced with increase of applied loading. Higher stress concentration ratio indicated lesser load on surrounding soil and therefore the soil settlement could be reduced.

Keywords: Compression; geotextile encapsulation; lime column; marine clay; stress concentration ratio

Abstrak

Tanah liat marin yang sering didapati di kawasan perairan pantai Malaysia, adalah bahan tapak pembinaan yang bermasalah. Penyelidik terdahulu melaporkan bahawa penstabilan menggunakan kapur boleh memperbaiki tanah liat dengan berkesan. Walau bagaimanapun, masalah seperti kehancuran kepala tiang dan pengenapan yang lebih bagi tanah pada bahagian atas tiang, sering berlaku akibat daripada kekurangan tekanan sisi pada tanah di bahagian atas tiang. Dengan itu, pembalutan dengan geotekstil telah dicadangkan untuk tiang kapur dalam kajian ini. Nisbah penumpuan tegasan adalah penting untuk memahami tingkah laku tanah distabilkan oleh tiang di bawah beban pengukuhan. Ujian pengukuhan dengan pembebanan berperingkat telah dijalankan atas tanah liat marin Pontian distabilkan dengan tiang kapur dibalut dan tanpa dibalut geotekstil. Nisbah penumpuan tegasan (σ_{mid}/ σ_{soil}) yang bermaksud tegasan di atas tiang (σ_{mid}) dibahagikan dengan tegasan di atas tanah sekitar (σ_{soil}), disiasat dalam setiap peringkat pembeban.Sampel diawet selama 14, 28 dan 56 hari sebelum diuji. Didapati bahawa nisbah penumpuan tegasan adalah bergantung kepada sifat-sifat kekuatan tiang kapur dan jumlah beban yang dikenakan. Pembalutan geotekstil telah meningkatkan nisbah penumpuan tegasan pada tiang kapur; kesan ini boleh dipertingkatkan lagi dengan menambah tekanan sisi pada tanah sekitar. Namun, kesan ini berkurangan dengan peningkatan beban pengukuhan. Nisbah penumpuan tegasan yang lebih tinggi menunjukkan kurang beban dikenakan pada tanah sekitar maka pengenapan tanah dapat dikurangkan.

Kata kunci: Pemampatan; pembalutan geotekstil; tiang kapur; tanah liat marin; nisbah penumpuan tegasan

1.0 INTRODUCTION

Marine clay is a problematic base material with low strength, low permeability and high compressibility which can cause continuous settlement and damages to foundation and structures above. It was widely encountered in many coastal areas in Malaysia. Many researchers reported that deep stabilisation using lime can effectively stabilise clayey soil [1-8]. However, insufficient confining pressure from the surrounding soil normally leads to the inferior performance on the upper part of column, for example: column head crushing and larger deformation for adjacent soil at top part of column [9-10]. Previous researches showed that the confining pressure provided by surrounding soil can improve the load bearing capacity of lime pile [11]. Geotextile encasement increased the confining pressure to granular column and therefore improved the settlement reduction by granular column [12-14]. Therefore,geotextile encapsulation was proposed for lime column. The stress distribution and concentration ratio are vital in the design analysis of columnar stabilised soil [15-16]. Higher vertical load on the top of column due to high stress concentration ratio might induce larger settlement and bulging on column [17]. Therefore, this study focused on the stress concentration ratio of Pontian marine clay sample stabilised with lime column at different ages, with and without geotextile encapsulation. Influence of geotextile encapsulation on stress distribution in the composite system was also evaluated.

2.0 EXPERIMENTAL

2.1 Materials

Pontian marine clay from Sg. Penerok T/Kiri in Pontian, Johor, Malaysia was selected in this test. The soil was oven-dried at 50 °C, crushed and sieved to pass 2 mm sieve. Pontian marine clay consisted of 39 % clay, 51 % silt and 10 % sand. The soil had particle density of 2.48 Mg/m^3 and pH value of 7. The liquid limit and plastic limit of Pontian marine clay was 62 % and 30 %, respectively. It was classified as clay with high plasticity (CH). Stabiliser selected was hydrated lime produced by Limetreats in Pasir Gudang, Johor. Hydrated lime had an average particle density of 2.36 Mg/m^3. From suitability of lime test,the hydrated lime-water mixture has a pH value of 12.58 after 24 hours, which had fulfilled the criteria for suitability of lime for soil stabilisation purpose[18]. The initial consumption of lime was 4.4 %, based on initial consumption of lime test [18]. This meant that a minimum amount of 4.4 % lime was needed to achieve pH of 12.4, which is highly alkaline. Highly alkaline condition is needed to increase the solubility of clay-alumina and clay-silica in clay which are the sources for pozzolanic reactions in lime stabilisation process. Geotextile with high tensile strength and drainage properties was required for lime column encapsulation in order to ensure it does not affect the drainage properties of young aged lime column. TenCate Polyfelt® PEC uniaxial geocomposite was chosen as it composed high modulus polyester fibres, attached to a continuous filament nonwoven geotextile backing, which combined reinforcement function with drainage properties [19]. TenCate Polyfelt® PEC uniaxial geocomposite was graded based on tensile strength from PEC 35 to PEC 230. In order to have moderate strength with minimum elongation at nominal strength, PEC50 was chosen as the encapsulation material for lime column. The properties of Geotextile are as shown in Table 1.

2.2 Multi Stages Loading Test Setup

Multi stages loading test was conducted to investigate the geotextile encapsulation effect on stress distribution in the composite sample. Unit cell concept was adopted in this model test. A single column was installed at the mid of clay confined in frictionless cylinder with a rigid base to represent the column influence zone in a group of 53 mm diameter columns installed vertically on a Pontian marine clay bed above hard stratum, in triangular pattern with spacing of 163 mm. Lime content was selected based on typical lime content in lime column reported by previous study, which was 10 % [7].

Table 1 Properties of Tencate Polyfelt® PE50

Properties	Unit	Value	Testing Method
Mass per area	(g/m²)	280	BS EN ISO 9864
Characteristic short-term strength (cd)	(kN/m)	17	BS EN ISO 10319
Seam strength	(kN/m)	14	BS EN ISO 10321
Water flow rate normal to the plane	(mm/s) (l/m²s)	65	BS EN ISO 11058
Water flow rate in the plane (20 kPa)	(10^{-7}m²/s) (l/mh)	30 11	BS EN ISO 12958

Figure 1 and 2 presents the setup for multi stages loading test. The model test cell had inner diameter of 210 mm, with the height of 400 mm. Two rigid permeable plates were placed each on the top and bottom of specimen in order to provide drainage. To ensure an identical settlement on surrounding soil and column, the load was applied from a piston with piston guide and shaft, by using pressurized-air from the air compressor with a cylinder and controller. Stresses acting on the surrounding soil and column were detected by two small earth pressure gauges as shown in Figure 1. The settlement was monitored by using a linear variable differential transducer throughout the test whilst the data was collected and recorded by using a data logger.

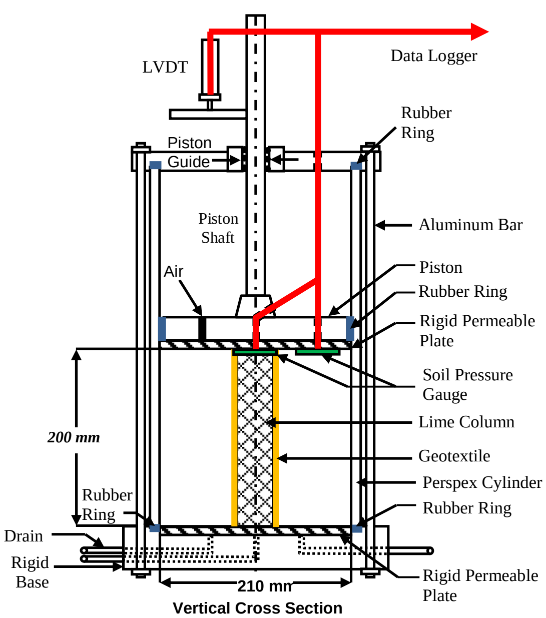


Figure 1 Test Equipment and Instrumentation Layout for MultiStages Loading Test

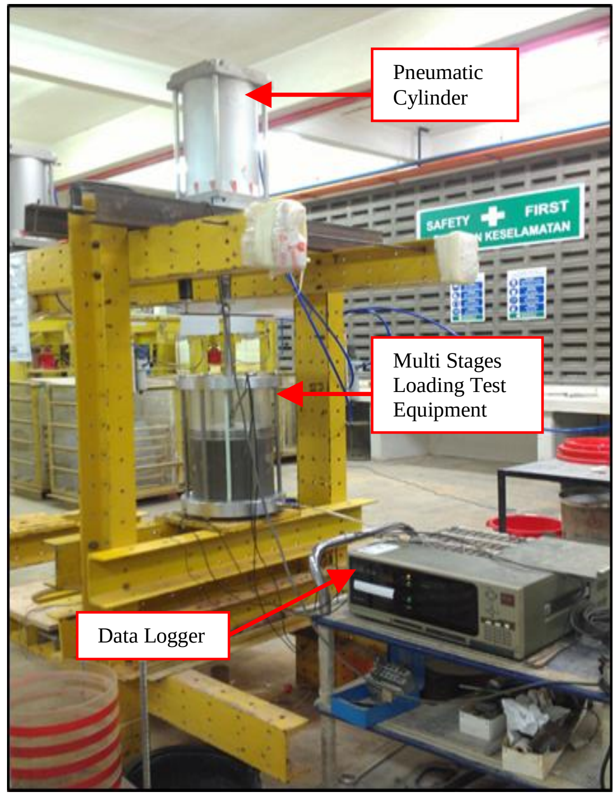


Figure 2 Test equipment for multi stages loading test

2.3 Preparation of Marine Clay Bed

Oven-dried Pontian marine clay was mixed with 72% of water and consolidated in the 200 mm diameter Perspex cylinder under 49 kPa for 3 days in order to form are moulded clay bed with undrained shear strength of about 20 kPa, at 200mm height. The undrained shear strength was verified by using Inspection Vane Tester, Geonor H-60.

2.4 Lime Column and GELC Installation

The lime column and GELC were prepared by compaction method, with lime content of 10 % and moisture content of 37 %.The 53 mm diameter lime column with 200 mm height was formed by three layers compaction of lime-soil mixture into a PVC tube. The bulk density of lime-soil mixture in column was 1.74 Mg/m³. Meanwhile the GELC was moulded by compaction of soil-lime mixture into a geotextile sleeve placed in a PVC tube. The geotextile sleeve was formed by sewing a 2.5 mm overlapped wide section of geotextile with prayer seam and 101 type of chain-stitch.

A sharp ended cylindrical steel tube was pushed into the middle of clay bed until required depth, together with a PVC tube as the casing. Then, the soil in the tube was removed and replaced with prefabricated column. The composite sample had a final height of210 mm, with a 10 mm thick soil pressure gauge on top of the 200 mm height column at middle of the sample. The side and top views of columnar stabilised soil is shown in Figure 3. The samples were cured for 14, 28 and 56 days at room temperature before tested.

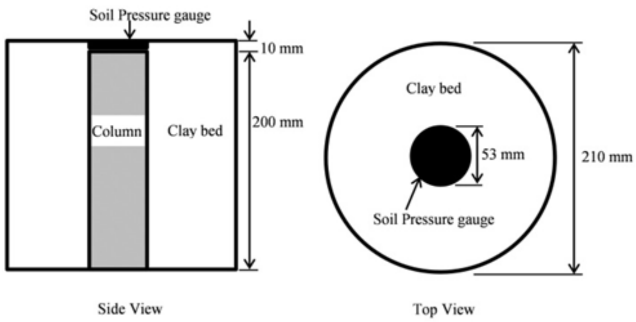


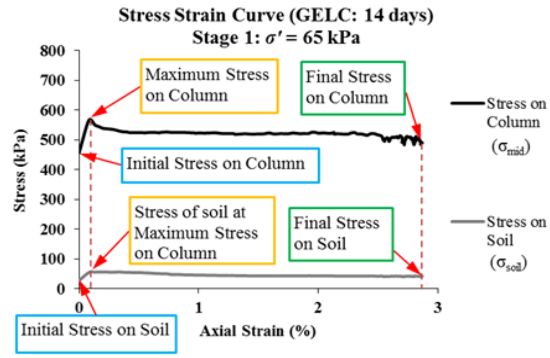
Figure 3 Side and top views of columnar stabilised sample

2.5 Multi Stages Loading Test Procedure

The sample was loaded in four stages, namely 65 kPa, 98 kPa, 147 kPa and 196 kPa by using an air-pressurized rigid piston. For each loading stage, the sample was loaded for 4 days until the deformation was smaller than 1 mm within 24 hours as an indication that 90 % consolidation was achieved. Stress on column and surrounding soil, settlement and time were observed. The samples tested were unstabilised Pontian marine clay and sample stabilised with lime column and GELC.

3.0 RESULTS AND DISCUSSION

The multi stages loading test on columnar stabilised clay was modelled according to unit cell concept. Stiffness of column was higher compared to surrounding marine clay; therefore it was expected higher stress will be concentrated on the column compared to surrounding soil. Stress concentration ratio was examined in each loading stage, namely: initial stress concentration ratio, final stress concentration, and maximum stress concentration ratio. The definition of stress ratios is as shown in Figure 4. Stress concentration ratio is defined as stress on column (σ_{mid}) divided by stress on surrounding soil (σ_{soil}). Initial stress concentration ratio is the stress concentration ratio immediate after compressive load was applied on sample at each loading stage whereas final stress concentration ratio is the stress concentration ratio at the end of each loading stage. Maximum stress concentration ratio is the stress concentration ratio when the column had highest stress during each loading stage.



Initial Stress Concentration Ratio
=Initial stress on column / Initial stress on soil
Final Stress Concentration Ratio
=Final stress on column / Final stress of soil
Maximum Stress Concentration Ratio
= Maximum stress on column/ Stress of soil at Maximum stress on column

Figure 4 Definitions of stress concentration ratios

3.1 Static Responses on Pontian Marine Clay

Initial and final stress concentration ratio of Pontian marine clay versus the applied loading in multi stages loading test are shown in Figure 5. The initial stress ratio for marine clay with different void ratio at each loading stage was ranged from 0.9 to 1.4; higher initial stress ratio was observed for marine clay with higher void ratio. Initial stress ratio decreased with the increase of vertical pressure as void ratio decreased with pre-consolidation pressures. The final stress ratio for Pontian marine clay at each loading stage ranged from 0.8 to 1.0. From the lab tests results, the unstabilised sample had initial and final stress ratio of near to 1, which showed that the stress concentration on the soil under loading area was almost similar; this could be explained by the same stiffness across the loading area within Pontian marine clay. However, slightly different of soil pressure at mid and surrounding was observed the soil contact pressure for cohesive soil under rigid foundation will not be distributed evenly under uniform load.

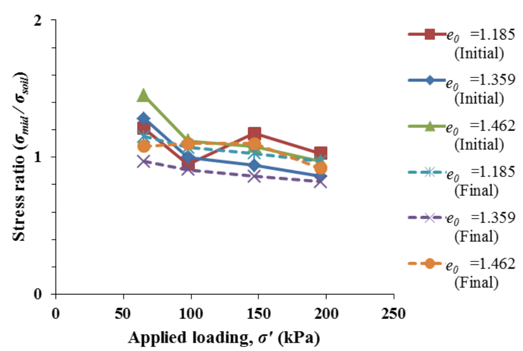


Figure 5 Stress ratios under different vertical pressures for Pontian marine clay

3.2 Static Responses on Lime Column Stabilised Pontian Marine Clay

The maximum stresses on column ($\sigma_{mid,max}$), initial and final stress concentration ratio for lime column stabilised sample cured for 14 and 56 days under different applied loading were discussed.

3.2.1 Maximum Stress on Lime Column

From multi stages loading test, the maximum stress on lime c olumn for lime column stabilised sample at each loading stage was plotted, as shown in Figure 6. The maximum stress on lime column at 14 days increased almost linearly with applied loading and reached 682 kPa at applied loading of 196 kPa. For lime column stabilised sample aged 56 days, the maximum stress on column had a sharp increase initially. However, when the applied loading is greater than 16 kPa, the increment became mild and reached 832 kPa at applied loading of 196 kPa.

The maximum stress on lime column in Pontian marine clay also increased with curing duration under respective applied loading. For sample with greater age (i.e. 56 days), the initial increment of stress on column respect to applied loading was higher and become mild afterwards as creep limit of lime column was exceeded. Lime column at greater age had higher stiffness thus would induce higher stress concentration on column under similar loading. The lime stabilised Pontian marine clay was in modification phrase and behaved inconsistently at age of 1 to 14 days from previous study [20]. Therefore, lime column stabilised sample at age of 14 days was categorized as young aged sample. For young aged sample, the maximum stress on column increased linearly but with a gentle gradient compared to greater aged sample at initial loading. Moreover the maximum stress on column for young aged sample was lower compared to sample at greater ages, under respective applied loading. The linear increase of maximum stress on column for young aged sample was due to strength gain during the consolidation process when the young column was yet to be matured. Loading on young aged lime column which are not yet mature could increase the strength of lime column [4].

3.2.2 Stress Concentration Ratio for Lime Column Stabilised Sample

Figure 7 and 8 shows the initial and final stress concentration ratios at each loading stage for lime column stabilised sample aged 14 and 56 days. Under vertical applied loading of 65 kPa at the first stage loading, the initial stress ratio of lime column stabilised sample aged 14 days was only about 6. As applied loading increased, the initial stress ratio increased to a peak of 15 under applied loading of 98 kPa; then it decreased to 9 under applied loading of 196 kPa. The final stress ratio was higher compared to initial stress ratio however it reduced as the applied loading increased. It fell below initial stress ratio at applied loading of 98 kPa and reached about 7 at applied loading of 196 kPa.

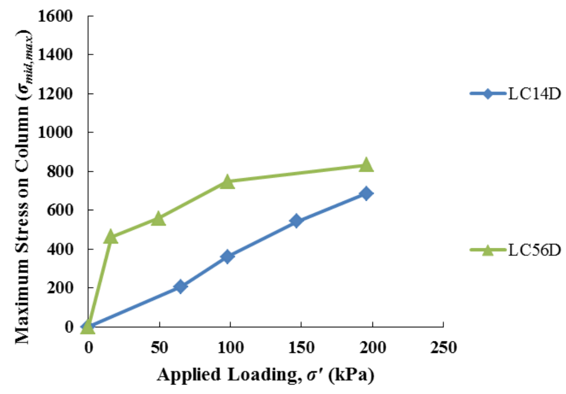


Figure 6 Maximum stress on column versus applied loading for lime column stabilised marine clay at different ages

Similar trend was observed for sample aged 56 days, with a higher peak in initial stress ratio. The initial and final stress ratio at first stage loading of 16 kPa was 26 and 32, respectively. The initial stress ratio increased to 32 at applied loading of 49 kPa and decreased to 10 at applied loading of 196 kPa. However, the final stress ratio decreased with the increasing applied loading; stress ratio of 5 was observed under applied loading of 196 kPa. From Figure 7and 8, the intersection between initial and final stress ratio for sample aged 14 and 56 days was at applied loading of 98 kPa and 25 kPa, respectively.

It was found that stress concentration ratio is a function of column materials strength properties and applied loading. The increase of stress ratio at each loading stage indicated that the applied vertical stress was transferred from surrounding soil to column. For sample at all ages, initially, load was transferred from surrounding soil to column. However, when applied load had exceeded the column material creep limit, the stress was transferred from column to surrounding soil. At this stage, the settlement was no longer dependent on column strength properties but was dominated by surrounding soil properties. Stress concentration ratio would reduce after a peak value due to the stress redistribution from column to surrounding soil and eventually reached a residual value, based on the results of monotonic undrained triaxial compression tests on columnar reinforced clay samples [21]. Furthermore, the stress concentration ratio would reduce after the column was failed, based on an axisymmetric model test on cement column stabilised Hong Kong marine clay [22].The pressure carried by the column and surrounding soil varied with time and applied loading under rigid foundation. The final stress on lime column increased with time and applied loading until a maximum value then reduced and fell below the initial stress on column at a specific loading stage. The intersection between initial and final stress ratio of lime column stabilised marine clay indicated the point at which stress on column had reached the creep limit of column material. Further increase of applied loading would initiate higher settlement on sample as the settlement would be dominated by surrounding soil properties. The intersection between initial and final stress ratio was observed to occur at lower applied loading for greater aged sample compared to younger aged sample. This might due to the higher stress concentration on column at same applied vertical pressure for column with higher stiffness, which had caused the stress on column to exceed the column material creep limit at lower applied loading.

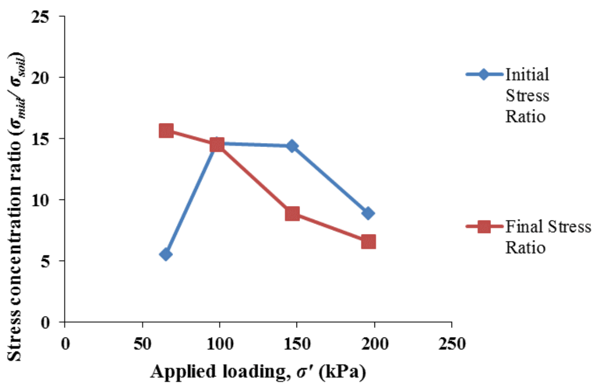


Figure 7 Variation of stress ratio versus total vertical pressure for lime column stabilised marine clay aged 14 days

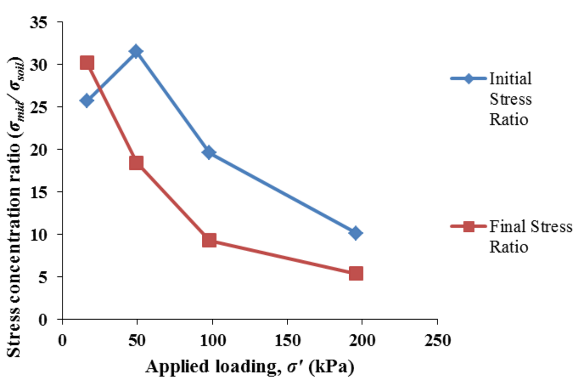


Figure 8 Variation of stress ratio versus total vertical pressure for lime column stabilised marine clay aged 56 days

3.3 Static Responses on GELC Stabilised Marine Clay

The maximum stress on column ($\sigma_{mid,max}$) and stress concentration ratio for GELC stabilised Pontian marine clay aged 14, 28 and 56 days were discussed.

3.3.1 Maximum Stress on GELC

From multi stages loading test, the maximum stress on GELC in Pontian marine clay at each loading stage was plotted, as shown in Figure 9. For sample at all ages, the maximum stresses on column at each loading stage increased with applied loadings on composite system. The maximum stresses at each loading stage for sample at elderly ages were higher compared to sample at younger ages. This was due to the strength of lime stabilised Pontian marine clay which increased with curing duration [23]. Vertical stresses tended to be distributed to material with a higher stiffness.

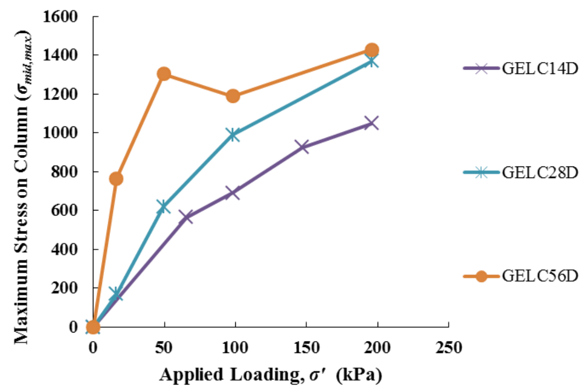


Figure 9 Maximum stress on column versus applied loading for GELC stabilised marine clay at different ages

3.3.2 Stress Concentration Ratio for GELC Stabilised Sample

Figure 10 to 12 presents the initial and final stress concentration ratios at each loading stage for GELC stabilised marine clay with different ages. Under vertical applied loading of 65 kPa at the first stage loading, stress ratio of sample aged 14 days was initially 10 and then increased to 12 at the end of loading stage. With additional vertical loads, the initial stress ratio increased until 11 under applied loading of 147 kPa and afterwards decreased to 8 under applied loading of 196 kPa. Meanwhile the final stress ratio decreased with the increasing applied loading. The intersection between initial and final stress ratio for sample at 14 days was at applied loading of 98 kPa.

For the sample aged 28 days, both initial and final stress ratio firstly increased with applied loading. However, the initial stress ratio started to decrease after applied loading of 98 kPa and finally reached 12 at applied loading of 196 kPa. Meanwhile the final stress ratio started to decrease after applied loading of 49 kPa and finally reached 7 at applied loading of 196 kPa. At applied loading of 90 kPa, initial stress ratio surpassed the final stress ratio.

The initial stress ratio for sample aged 56 days initially increased and then decreased after applied loading 49 kPa and finally reached 20 at applied loading of 196 kPa, whereas final stress ratio decreased with the increasing applied loading and reached 11 at applied loading of 196 kPa. The intersection between initial and final stress ratio for sample aged 56 days was at applied loading of 25 kPa.

For sample at all ages, initially, load was transferred from surrounding soil to GELC. Afterwards when applied load had exceeded the column material creep limit, the stress was transferred from column to surrounding soil. At this stage, settlement was no longer dependent on lime column strength properties but was dominated by surrounding soil properties.

The intersection between initial and final stress ratio was observed to occur at lower applied loading for sample with elder age compared to younger age. This might due to higher stress concentration on column at same applied vertical pressure for GELC with higher stiffness, which caused the stress on column to exceed column material creep limit at lower applied loading.

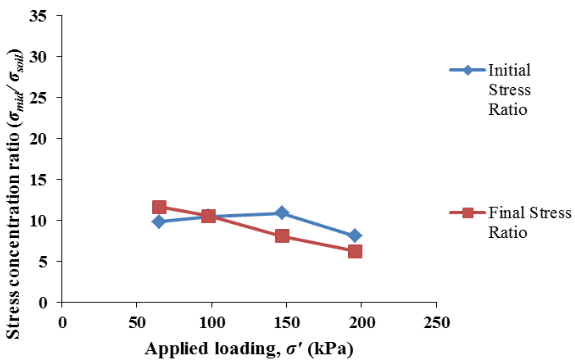


Figure 10 Variation of stress ratio versus applied loading for GELC stabilised marine clay aged 14 days

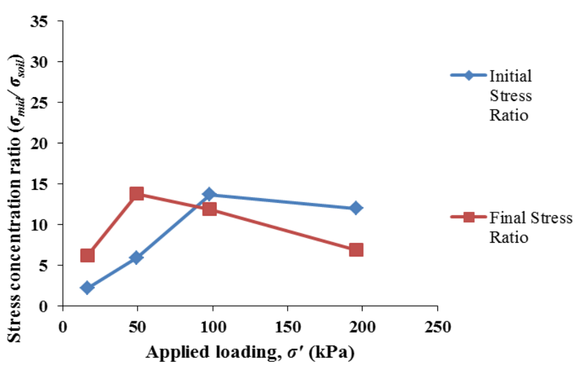


Figure 11 Variation of stress ratio versus applied loading for GELC stabilised marine clay aged 28 days

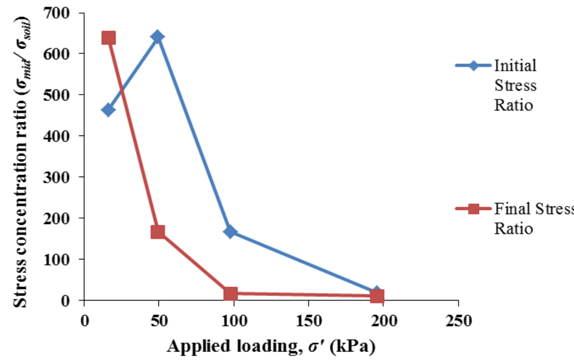


Figure 12 Variation of stress ratio versus applied loading for GELC stabilised marine clay aged 56 days

3.4 Comparison on Static Responses of Lime Column and GELC Stabilised Pontian Marine Clay

Figure 13 shows comparison on the maximum stress on column at each loading stage for lime column and GELC stabilised soil. It was observed that the maximum stress on column for GELC stabilised sample at all ages was higher compared to lime column stabilised sample under similar loading. This showed that geotextile encapsulation increased the stiffness of lime column and induced higher load concentration on column.

Comparison on stress ratio at maximum stress on column between lime column and GELC stabilised Pontian marine clay sample tested after different curing periods is shown in Figure 14. For both lime column and GELC stabilised samples at younger ages such as 14 days, the stress ratio initially increased to a peak and then reduced as the applied loading increased. For both lime column and GELC stabilised samples aged 56 days which had stiffer column, stress ratio decreased as the applied loading increased. Initially, the stress ratio of GELC stabilised sample was higher compared to lime column stabilised sample. However, as applied loading increased, the variation on stress ratio lime column and GELC stabilised sample decreased. Decrease of stress ratio was due to the high applied loading which exceeded column material creep limit and the loads started to transfer from column to surrounding soil.

Comparison on the stress at intersection of initial and final stress ratio for lime column and GELC stabilised Pontian marine clay sample tested after different curing periods is shown in Table 2. However, the sample for LC at 28 days was spoilt. Therefore, it was decided to remove both the LC and GELC samples aged 28 days from the table. It was found that for both lime column and GELC stabilised sample, sample at greater ages had lower intersection point between initial and final stress ratio compared to sample at younger ages. Increase of lime column strength hastened the transfer of stress from column to surrounding soil as more load would be concentrated on stiffer column at elder ages under similar applied loading compared to column with lower strength at younger ages. The intersection point between initial and final stress ratio for both lime column and GELC are similar for sample at respective age. This indicated that geotextile encapsulation did not affect the starting point of stress transfer from column to surrounding soil although higher load was concentrated on GELC compared to lime column at respective applied loading.

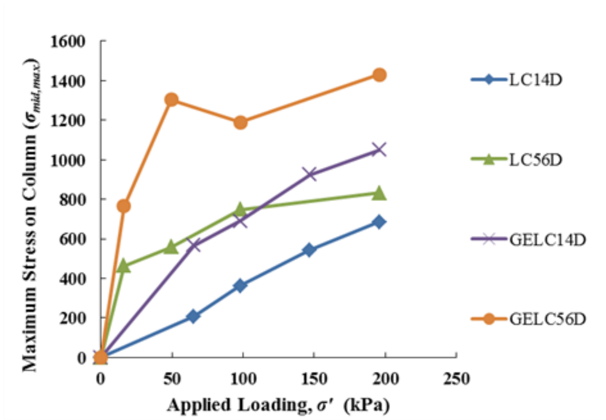


Figure 13 Maximum stress on column at each loading stage versus total vertical pressure for lime column and GELC stabilised marine clay at different ages

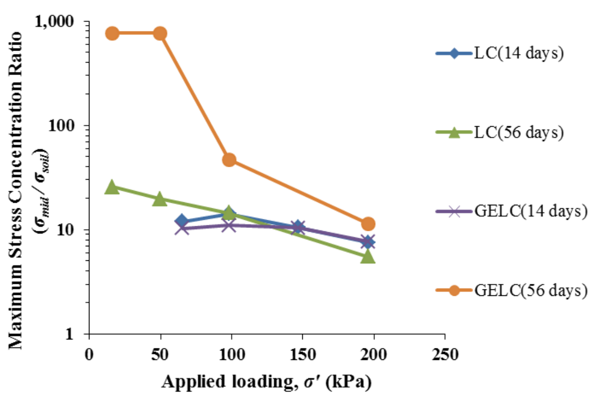


Figure 14 Stress ratio at maximum stress on column versus applied loading for lime column and GELC stabilised Pontian marine clay with different ages (σ'_p = 49 kPa)

Table 2 Effects of curing duration and geotextile encapsulation on load transfer from the column to the surrounding soil

Age (days)	Pre-consolidation Pressure, σ'_p (kPa)	Applied Loading at Intersection of Initial and Final Stress Ratio (kPa)	
		LC	GELC
14	49	98	98
56	49	25	25

3.5 Effect of Confining Pressure by Surrounding Soil on the Static Response of Columnar Stabilised Soil

Multi stages loading tests were conducted on lime column and GELC stabilised samples with marine clay of higher stiffness. The Pontian marine clay bed was prepared by consolidation of marine clay slurry with moisture content of 72 % under pressure of 98 kPa for 3 days, in order to form a soft to firm marine clay bed with undrained shear strength about 40 kPa. Columns of similar properties as previous tests were installed in the centre of clay bed and cured for 14 days before tested. The maximum stresses on column at each loading stage and stress ratio changes due to the increase of surrounding soil stiffness were investigated.

The maximum stress on column at each loading stage for columnar stabilised Pontian marine clay with different pre-consolidation pressure on surrounding clay was plotted, as shown in Figure 15. For lime column in Pontian marine clay pre-consolidated under 98 kPa, the maximum stress on column at each loading stage was initially higher compared to lime column in Pontian marine clay pre-consolidated under 49 kPa. However, as the applied loading increased, the maximum stress on column merged together at applied loading of 100 kPa. As the surrounding soil underwent strength gain in consolidation process, confining pressure by surrounding soil also increased with loading stages. Hence, the maximum stress on column for samples with surrounding soil pre-consolidated under different pressures merged eventually as the applied loading increased. Previous researcher found that the undrained shear strength of lime and cement treated soil at low confining pressure was inferior to samples at high confining pressure; nevertheless the undrained shear strength of stabilised soil become almost constant when the total confining pressure exceeded 150-250 kPa, which was equal to half of unconfined compressive strength of stabilised sample [24]. Meanwhile for GELC in Pontian marine clay pre-consolidated under 98 kPa, the maximum stresses on column at all loading stages were higher compared to lime column in Pontian marine clay pre-consolidate under 49 kPa. The confining pressure by surrounding soil increased the stiffness of lime column; however the effect was reduced in eventually eliminated when the applied loading exceeded the creep limit of lime column. The geotextile encapsulation successfully increased the stiffness of the lime column thus higher maximum stresses was observed on GELC, and this effect was further enhanced by the confining pressure provided by the surrounding soil. This could be supported by previous researcher's findings on from an analytical procedure based on the cavity expansion method. The circumferential tensile stress developed in encapsulation material during bulging of granular column could enhance the stiffness and strength of granular column, attributed the counter reaction by surrounding soil against the enlargement of granular column [14].

The initial and final stress ratios at each loading stage for lime column and GELC stabilised sample with different pre-consolidation pressure on surrounding soil are shown in Figure 16 and Figure 17, respectively. Initially, final stress ratio for both lime column and GELC stabilised sample were higher compared to initial stress ratio. Afterwards, final stress ratio decreased and dropped below the initial stress ratio as applied loading increased.

All initial and final stress ratios for GELC stabilised sample were higher than lime column stabilised sample, except the stress ratio at first loading stage. However, the stress on GELC at first loading stage was higher compared to lime column stabilised sample. More stress was concentrated on GELC compared to lime column. Increase of confining pressure by surrounding soil increased the stress ratio for both lime column and GELC stabilised clay. This indicated that confining pressure enhanced the stress concentration on column which could reduce the loading on surrounding clay. Geotextile encapsulation increased the stress concentration on lime column and it was further enhanced by confining pressure of surrounding soil.

The intersection point of initial and final stress ratio occurred at applied loading of 95 kPa for both lime column and GELC stabilised Pontian marine clay sample aged 14 days. Table 3 shows the stress at intersection of initial and final stress ratio for lime column and GELC stabilised Pontian marine clay with different pre-consolidation pressure on surrounding soil. It was observed that for sample with pre-consolidation of both 49 kPa and 98 kPa on surrounding soil, the applied loading at the point which load transfer from column to surrounding soil started was similar. Confining pressure provided by both geotextile encapsulation and surrounding soil did not influence the starting point of stress transfer from column to surrounding soil for lime column stabilised Pontian marine clay.

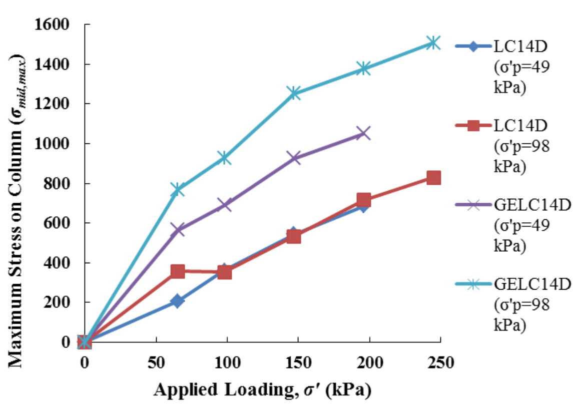


Figure 15 Maximum stresses on column versus total vertical loadings for columnar stabilised marine clay with surrounding soil pre-consolidated under different pressures

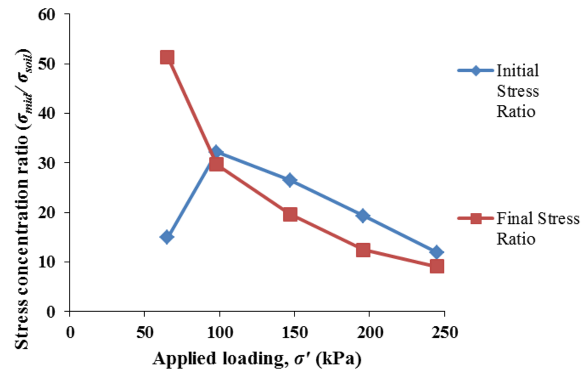


Figure 16 Variation of stress ratio versus total vertical pressure for lime column stabilised Pontian marine clay aged 14 days with surrounding soil pre-consolidated under 98 kPa

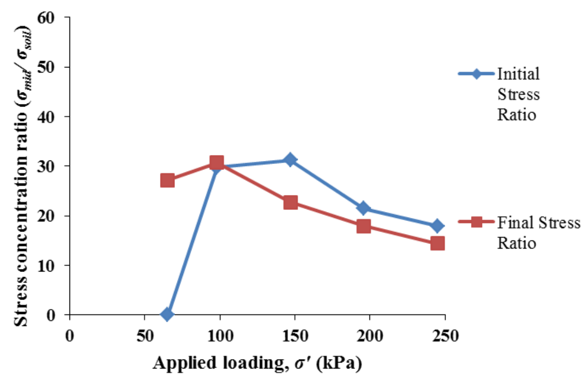


Figure 17 Variation of stress ratio versus total vertical pressure for GELC stabilised Pontian marine clay aged 14 days with surrounding soil pre-consolidated under 98 kPa

Table 3 Effects of pre-consolidation pressure of surrounding soil and geotextile encapsulation on load transfer from the column to the surrounding soil

Age (days)	Pre-consolidation Pressure, σ'_p (kPa)	Applied Loading at Intersection of Initial and Final Stress Ratio (kPa)	
		LC	GELC
14	49	130	98
14	98	125	95

4.0 CONCLUSION

The stress concentration ratio was a function of column materials strength properties and applied loading. The stress concentration ratio for unstabilised Pontian marine clay sample was near to 1 as the stiffness across loading area within the sample was similar. The stress concentration ratio increased with sample curing duration as the lime column stiffness increased with ages. The confining effect by geotextile encapsulation increased the stress concentration ratio of sample; however the effects reduced with the increasing applied loading. Additionally, the increase of stress concentration due to geotextile encapsulation was enhanced by confining pressure of surrounding soil. Higher stress concentration indicated that more load was distributed to column and therefore the loading on surrounding soil was reduced and the soil settlement could be reduced.

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