DEVELOPMENT OF A NEW CONSOLIDATION TEST FOR SOIL-CEMENT COLUMNS TREATED GROUND

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Abstract

In this study, Medium Rapid Consolidation Equipment (MRCE) was developed to determine the settlement behaviour of soft ground treated by soil-cement columns. MRCE operates based on Constant Rate Strain (CRS) consolidation theory, which is a continuous loading method of testing that can accelerate the consolidation process of cohesive soil as compared to the conventional Oedometer and Rowe cell tests. Since the stiffness of soil-cement columns increases with time, the CRS concept is the best method to determine the settlement at a particular time. Several modifications were made on the MRCE including the introduction of a back pressure system to further saturate the soil and measurement of excess pore water pressure. Four tests with varied values of the area of improvement were carried out using the MRCE to investigate settlement behaviour of stabilized soft soil. It was found that by increasing the area of improvements ranging from 15.3% to 30.7%, the strain rates improved from 41% to 53% compared to untreated soil. To conclude, the MRCE was able to quantify the consolidation characteristics of the stabilized soil with varying values of the area of improvements into a comparable settlement reduction factor.

Keywords: **Medium Rapid Consolidation Equipment, Constant Rate Strain (CRS), Soil-cement, Area of improvements, Consolidation characteristics, Settlement reduction factor, Ground improvement**

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Introduction

Deep Soil Mixing (DSM) is a popular method to stabilize soft ground since it has been introduced in the early 1970s. DSM is a term where the in-situ soil is mixed with binding agents such as lime or cement in a powdery or slurry form with the main goal to improve volume stability, strength, permeability, and durability of the soil (Porbaha, 1998; Terashi and Juran, 2000; Horpibulsuk *et al.*, 2004, 2011; Arulrajah *et al.*, 2009, 2018; Chu *et al.*, 2009a, 2009b; Dehghanbanadaki *et al.*, 2013; Shen *et al.*, 2013; Awg Shahminan *et al.*, 2014; Raftari *et al.*, 2014; Rashid *et al.*, 2013, 2014, 2015a, 2015b, 2016, 2017a, 2017b; Phetchuay *et al.*, 2016; Yaghoubi *et al.*, 2018). Numerous studies have been done to determine the ultimate bearing capacity of soft clay treated with DSM under vertical load using physical modelling, numerical modelling, or full-scale field test (Kitazume, 1996; Karastanev, 1997; Omine *et al.*, 1999; Kitazume and Terashi, 2002; Bouassida and Porbaha, 2004a, 2004b; Porbaha *et al.*, 2004; Fang, 2006; Yin and Fang, 2006). The higher natural water content of soil normally results in the lower bearing capacity and higher settlement for the same input of cement (Mohammadinia *et al.*, 2019; Disfani *et al.*, 2021). However, minimal effects have been directed towards the study of settlement behaviours and most of the studies are using 1-Dimensional consolidation cell tests (JICE, 1999; Ishikura *et al.*, 2005, 2007, 2016; Chai *et al.*, 2010; Chai and Pongsivasathit, 2010; Gong *et al.*, 2015; Horpibulsuk *et al.*, 2012).

Although some researchers (Lorenzo and Bergado, 2003; Chai *et al.*, 2010) have proposed equations for the settlement calculation of DSM stabilized ground, however, their results were based on the incremental loading method. They have ignored some aspects such as the effects of the curing period and vertical drainage of natural soft soil. According to their studies, the important parameters that affect the improved ground by a group of the floating column are area improvement ratio (a_p0, column height (H_c), and soft soil thickness (H), column strength (c_{uc}), strength of surrounding soil (c_{us}), stress concentration ratio (η) and load intensity (P) (Yao *et al.*, 2016). Since the stiffness of soil-cement columns increases with time, the Constant Rate Strain (CRS) concept is the best method to determine the settlement at a particular time (Kassim and Clarke, 1999).

Therefore in this study, new consolidation equipment was developed based on the CRS concept to determine the settlement behaviour of soft clay treated by a group of the soil-cement column formed by DSM and named as Medium Rapid Consolidation Equipment (MRCE). This is more suitable for the stabilized soil whose soil strength is influenced by the curing period (Kassim and Clarke, 1999). Therefore, the consolidation characteristic could be determined at the actual curing period. MRCE was used to conduct several consolidation tests to determine settlement behaviours of DSM stabilized ground under various improvement area ratios. This study developed the relationship of void ratio, e against vertical effective stress, σ' which contributes to the determination of compression index, c_c value. For the MRCE test, the strain rate, *r* used in this study was determined based on Lee, (1981) approach as listed in Equation (1) (Kassim *et al.*, 2014; 2016; Raftari *et al.*, 2014).

$$\beta = \frac{rH_o}{c_v} \qquad (1)$$

where β is the normalized strain rate H_o is the sample's height and c_v is the average coefficient of consolidation. The c_v values from the conventional oedometer test were used to estimate the strain rate before the CRS test. Based on the obtained results, the settlement of the stabilized soil by the effects of area of improvement can be quantified and proposed with a series of equations.

Materials and Methods

Design of MRCE

A new CRS chamber named MRCE was designed. Major components of the MRCE are the top cap, aluminium cylinder, perforated plate, and base plate. All parts of the MRCE were made using a rigid aluminium metal. Figure 1. shows the general schematic of the MRCE cell. The MRCE has an internal height of 400 mm and a diameter of 230 mm to accommodate the final height of the ground sample at 200 mm and a maximum of 6 soil-cement

Figure 1. **MRCE setup in the TRI-SCAN advance loading frame**.

columns respectively. The MRCE was mounted on the strain control load frame. The cell was assembled using a three-bolt system. Latex o-rings were used to prevent the leakage from gaps between the base plate and the cylinder. The circular groove was created in the base plate to assist the drainage of water from the cell. The top cap has sealed holes used to allow a miniature pore pressure transducer to be installed inside the cell. The loading piston was sealed with two rubber o-rings during the settlement sample testing. Similar circular grooves were implemented on the loading piston to assist the drainage of water. A thin layer of grease was applied on the loading piston to minimized the friction along the side of the loading piston and chamber during the loading test.

A soft model ground was prepared in the MRCE cell by applying a maximum pressure of 50 kPa during the preparation. A pair of porous paper was placed on the top and bottom parts of the specimen within the aluminium cylinder. A perforated loading platen was placed on top of the specimen through which the back pressure was applied. This ensured that the consolidation of the sample occurred only within the cylinder and the back and pore water pressures in the top and bottom parts could be different. Since the consolidation test on soil-cement column improved ground was conducted in the smooth model tank, the effect of the boundary condition on size of the soil-cement column is insigbificant. Backpressure and pore pressure transducers were filled using o-rings and installed on the top cap and base plate, respectively to measure the pressures. In addition, 3 pore pressure transducers were installed at different heights at the cell surface to measure the development of pore pressures at 50 mm, 100 mm, and 150 mm from the cell base. A loading piston was used to transfer the load from the Pneumatic Cylinder to the loading platen and specimen. A pneumatic cylinder with a maximum air pressure of 10 bar or 1000 kPa was used. Constant air pressure was supplied by a mobile air compressor suited with the pneumatic cylinder. A dial gauge was used to measure the amount of pressure supplied from the air compressor to the pneumatic cylinder. A 10 kN S type load cell, which was mounted between the pneumatic cylinder shaft and loading piston shaft, was used to confirm the same amount of pressure transmitted from the pneumatic cylinder to the loading platen. The pneumatic cylinder was firmly attached to the centre of the loading frame using 4 steel bolts.

In preparation of soil-cement columns, several devices were designed and fabricated. A 50 mm in diameter aluminium tubes with 100 mm height was used to cure soil-cement mixtures for 9 days to achieve the desired soil strength. In this study, the targeted strength for the soil-cement column was 36 kPa which results in a low strength ratio between soil-cement column with surrounding soil (Rashid *et al.*, 2015a, 2015b, 2017a). 10% of ordinary Portland cement (OPC) derived from a kaolin dry mass were used, which are a typical range of OPC used in practice (Rashid *et al.*, 2015a, 2015b, 2017a; Suksiripattanapong *et al.*, 2021). A special set of aluminum templates was fabricated to install the group columns under a different improvement area ratio of 15%, 20%, and 30% by 3, 4, and 6 columns respectively. The column tubes and templates are shown in Figure 2. A handy extruder piston was designed to remove soil-cement columns from the aluminium tubes as shown in Figure 3. Soil remover devices consisted of two parts, which were the sharp-tipped aluminium tube, and its case to the borehole in the model ground with variable heights as shown in Figure 4. These aluminium tubes had a length of 200 mm with an outside diameter

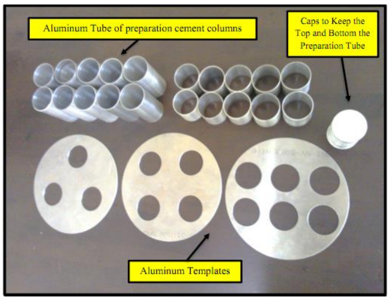

Figure 2. Aluminum tube and template.

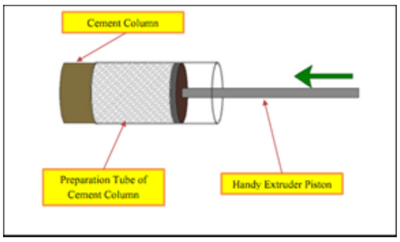

Figure 3. Extruder mechanism to extrude the column.

Figure 4. Soil remover devices.

of 52 mm and contained a 2 mm thickness of wire at its end to cut the soil model.

After the preparation of the ground model was completed using the pneumatic cylinder, the modified beam of the mechanical loading frame was mounted on the loading frame. A mechanical loading frame with a constant motor drive of 0.0001 to 9.9 mm/min was used for the CRS as shown in (See Figure 1). A modification of the main beam in the mechanical loading frame was designed and fabricated so that it could fit the load cell during the CRS test as shown in Figure 5. Four measuring devices were used in the CRS test for data measurement. The arrangement of measuring devices including load cell, linear variable displacement transducer (LVDT), pore water pressure transducer, and pressure transducer are schematically shown in Figure 6.

A 30 mm LVDT with an accuracy of 0.01 mm was used to measure vertical displacement. The pressure applied to the specimen was measured using an S-type load cell with a capacity of 10 kN and an accuracy of 0.04 kN. In addition, measuring the pore water and back pressures of the MRCE was done using five pressure transducers with a capacity of 1500 kPa and an accuracy of 0.1 kPa. Stresses on the cement columns and the surrounding soil were measured using waterproofed miniature pressure transducers with a 6.5 mm diameter and 1 mm thickness.

System Calibration

The load cell and Linear Variable Displacement Transducer (LVDT) were calibrated using incremental loading from the load frame and digital calliper, respectively. Calibrations were done twice during the main test, which was at the beginning and in the middle of testing. These calibrations proved to be linear with an accuracy of less than 0.1%. The backpressure and pore pressure transducers were calibrated using an Advance Pressure/Volume Controller (ADVDPC) connected to a computer. Microprocessor-controlled screw pumps were used to accurately measure the hydraulic pressure and volume variations. Variations of pore water pressure ranged from 0 to 50 kPa. Results of the calibrations showed a linear relationship between the applied pore pressure and recorded pore pressure with R^2=1. The miniature pressure transducer was calibrated in a sealed Triaxial cell filled with water as shown in Figure 7. The maximum pressure of 200 kPa was applied to the triaxial cell and data was collected. According to Labuz and Theroux (2005), calibration factors from the fluid calibrations were susceptible to 20% divergence because of the non-uniform contact stress or arching effect. A reduction of about 20% was applied and the accuracy of R^2 = 1 was determined from the miniature pressure transducer.

Preparation of Soil Sample

The soil-cement columns were prepared using brown kaolin powder mixed with variable mixtures of ordinary Portland cement (OPC). Meanwhile, the ground model was prepared using the brown kaolin. Table 1. shows the characteristic of kaolin used for the study. Classification of the kaolin was based on the British Soil Classification System (BSCS) (British Standard 1377, 1990). Two stages of preparation were needed for the test namely the ground soil preparation and the installation of the cement columns in the model ground.

For the preparation of the ground model, 10 kg of 24 h oven-dried kaolin powder was mixed with

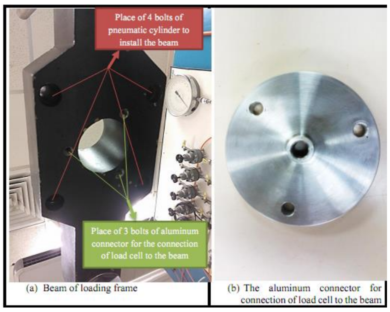

Figure 5. The beam and its paraphilia.

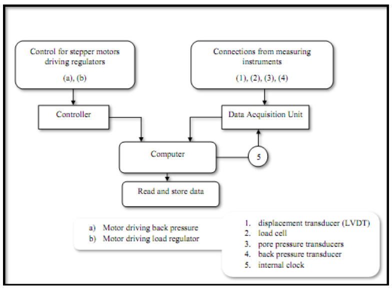

Figure 6. Schematic arrangement of a control system for CRS tests.

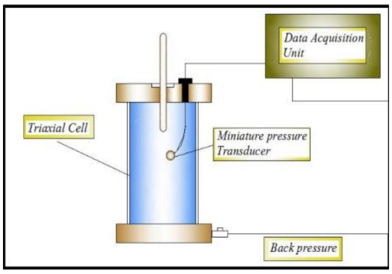

Figure 7. Schematically setup view of soil pressure transducer calibration.

Table 1. Characteristics of Kaolin clay.

Properties	Characteristic values
Liquid limit	54 %
Plastic limit	30 %
Plasticity index	24 %
Specific gravity	2.60
Classification	CH

Figure 8. Stage preparation of soil-cement columns.

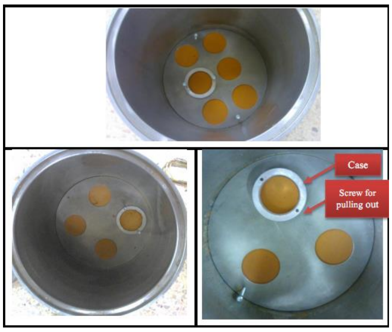

Figure 9. The templates of soil-cement columns in the model ground.

deionized water at twice the liquid limit of kaolin to produce a homogenous soil sample. As a result, 10.8 litres of distilled water was used. The slurry mix was poured into an O-ring sealed MRCE chamber greased with silicon and fitted with two layers of Vyon porous plastic. One dimensional consolidation method was selected for the preparation of the ground model with an undrained shear strength of 10 kPa under overconsolidation ratio, OCR of 10. Consolidation started with the self-weight of the consolidation piston applied for 2 days followed by a continuous load of 1.5 kPa, 3 kPa, 6 kPa, 12.5 kPa, 25 kPa and 50 kPa for 24 h respectively. The loading was decreased to 5 kPa for one day to prepare an overconsolidated sample obtained at OCR of 10 and 200 mm of ground model height. The overall preparation of the ground model was around 12 days.

Prior to the ground model preparation, soil-cement column preparation was done using a food mixer mixing a variable percentage of OPC with 108% of de-aired water and kaolin powder. Column mould with 52 mm diameter and 100 mm height was used to prepare the soil-cement columns. Preparations of the soil-cement column are shown in Figure 8. The slurry was poured into a sealed column mould and cured for 9 days at room temperature. After the soil-cement columns were cured, the extruder was used to extrude the column from the mould. Three, four, and six holes templates were used for this test as shown in Figure 9.

During the soil-cement column installation, sharp-tipped aluminium tubes and their case were fitted into the template, and 100 mm depth of soil was carefully removed from the model ground (according to the soil-cement height). The soil-cement columns were carefully put inside the ground hole. A miniature pressure transducer (MPT) was fitted at 3 places: the bottom part of the cement column, the top part of the cement column, and the soil surface as shown in Figure 10. After the aluminium templates were removed, two porous plastic paper layers were placed on top of the specimen and the chamber cap was closed. A surcharge of 50 kPa was reapplied to the model ground to eliminate gaps between the soil column and the surrounding clay during soil-cement column installation for another 24 h in preparation for the testing procedure.

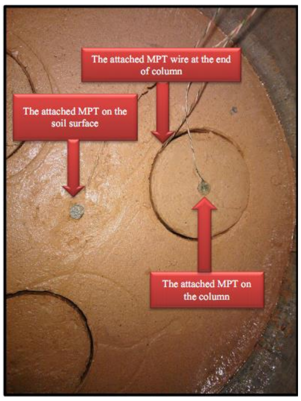

Figure 10. The position of the Miniature pressure transducer (MPT).

Table 2. List of physical modeling test.

No	Name test	Percentage cement	Area improvement	Number of columns
1	untreated	0	0	0
2	C10-N3-L10	10	15.33	3
3	C10-N4-L10	10	20.45	6
4	C10-N6-L10	10	30.67	9

Test procedure

In this study, 4 major tests have been conducted for 3 groups of a constant variable (which are; constant 0.02 mm/min sets of rate of strain, 10% of cement ratio, and 0.50 depth/length columns) and for 3 various sets of an area of improvements. The complete lists of the small-scale physical modelling test are shown in Table 2. The strain control speed was then set and a data record was done every 10 minutes until the penetration reached approximately 20 mm penetration to represent a strain of 10% of the total height of the ground model. Figure 11. shows the setup of the MRCE and the equipment, which was set up for physical testing. After the consolidation process was completed, the vane shear test was performed on the surrounding soil to measure soil strength. The testing was conducted immediately after the loading platen was removed.

Results and Discussion

CRS test result and discussion

To investigate the consolidation behaviour of composite model ground, the void ratio versus vertical effective stress (e-log σ') relationship was plotted. Figure 12. shows the e-log σ' relationship for 10% cement, length/depth ratio of 0.5 (100 mm soil-cement column) and various areas of improvement which were 15.3%, 20.4% and 30.7%. The untreated soil was used as a reference to evaluate the settlement improvement of the composite ground. In general, by increasing the area of improvement, the void ratio curve shifted towards the effective stress region causing the increase of deflection per the increase of the area of improvement. It also showed that at the highest effective stress, the highest void ratio was obtained at the highest improvement area which indicated that the treated ground stiffness increased with an increase of the improvement area ratio. In addition, it can also be determined that by increasing the area of improvement of the soil-cement columns, the compressibility index, C_c, of the stabilized clay decreased. Figure 13. shows the effect of various areas of improvement on the stress-strain curve with a constant 10% cement and length/depth ratio of 0.5 This supported the findings that the increase in the area of improvement reduced the vertical deformation on the composite ground. The effect from the area of improvement improved the average strain of the composite ground from 41% to 53%. The variation of pore water pressure at the bottom of the soft ground model was measured as a maximum value according to the one-way

Figure 11. Setup of the MRCE and equipment for the physical testing.

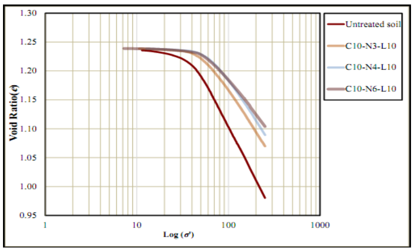

Figure 12. The effect of improvement ratio on e-log σ_v curve for 10% cement and length/depth ratio of 0.50.

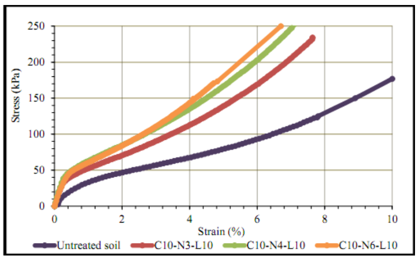

Figure 13. The effect of improvement ratio on the stress-strain curve for constant 10% cement and length/depth ratio of 0.50.

drainage system at the top of the specimen. As shown in Figure 14, the pore water pressure increased sharply and reached a peak and after that, it was approximately constant over time which is a similar finding with Ahmadi *et al.*, (2011). It is shown that the stability condition is achieved when the pore pressure becomes slightly stable in terms of magnitude after the increment of load. The ratio of excess pore water pressure to vertical effective stress, (u/σv'), versus effective stress for CRS consolidation of stabilized kaolin clay obtained from the laboratory tests is shown in Figure 15. The curve of u/σv' has moved up when the stress less than consolidation yield pressure, Py, and then continuously decreased with increasing of the effective stress. As clearly observed, u/σv' ratio of the all stabilized kaolin with the group of cement columns was less than 0.3 suggested by ASTM, (1982). Furthermore, it was observed that u/σv' ratio for the all stabilized kaolin was less than the suggested ratio by Lee, (1981) of 0.15 when the effective stress was more than 150 kPa. As the common range of consolidation stresses for DSM improved projects is in the range of 200 to 250 kPa (Özgen, 2011), it can be considered as an acceptance criterion of the constant rate of strain consolidation test.

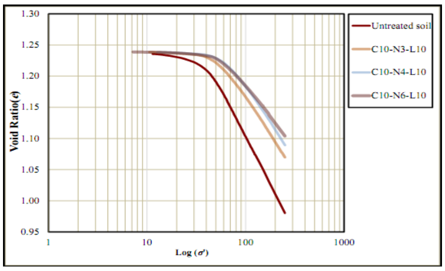

Figure 14. The variation of pore water pressure at the bottom of specimen versus elapsed time.

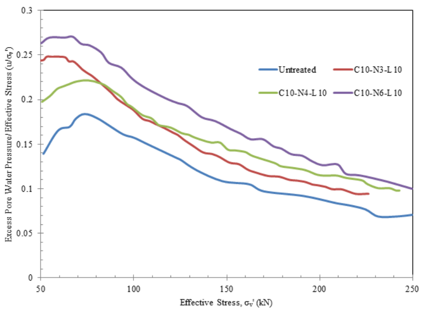

Figure 15. The ratio of excess pore water pressure to vertical effective stress, (u/σ') versus effective stress for stabilized kaolin clay at various improvement characteristics.

Figure 16. shows the general pore water pressure of the surrounding soil with relative depths. Overall, the pore pressure increased linearly with depth after being loaded with various consolidation stresses. In addition, pore water pressure increased when the applied consolidation stress was increased. Changes in the pore water pressure were present, which were believed to be due to the transmission of stresses to the lower layers of the soil-cement columns as reported by (Jiang *et al.*, 2014).

Settlement reduction factor, $F_{sr(Suntreated/Streated)}$ is defined as the ratio of the untreated soil settlement to the treated soil settlement. This factor was acquired to estimate the settlement of treated soil by multiplying conventional settlement calculations with the factor F_{sr}. The result for the F_{sr} for the constant cement value of 10%, length/depth ratio of 0.50, and various areas of improvement is presented in Table 3. From the F_{sr} approach, the final settlement of the treated soil under cement value of 10%, length/depth ratio of 0.50, and area of improvement between 15% to 30% could be estimated well.

Conclusion

From the study, the following conclusions can be drawn up based on the investigation of the effect of various areas of improvement of soil-cement column stabilization technique and are listed below.

i. A new CRS equipment to perform the study on the consolidation settlement of stabilized kaolin by a group of soil-cement columns was developed.
ii. By increasing the area of improvement of the soil-cement column, the value of compressibility index C_c and settlement value decreases.

Table 3. The equation of the settlement reduction factor under stress level.

Cement content (%)	Improvement details: Area improvement ratio (%)	Improvement details: Length/depth improvement (L/D)	Settlement reduction factor (F_{sr}) on the consolidation stress(σ')
10%	15.33	0.5	F_{sr}=7.0311(σ')$^{-0.275}$
10%	20.44	0.5	F_{sr}=33.337(σ')$^{-0.551}$
10%	30.66	0.5	F_{sr}=19.825(σ')$^{-0.433}$

iii. The effects of varying areas of improvement of soil-cement column stabilization technique can be quantified into an equation (Table 3).

iv. The range of improvement of average strain was ranged from 41% to 53%.

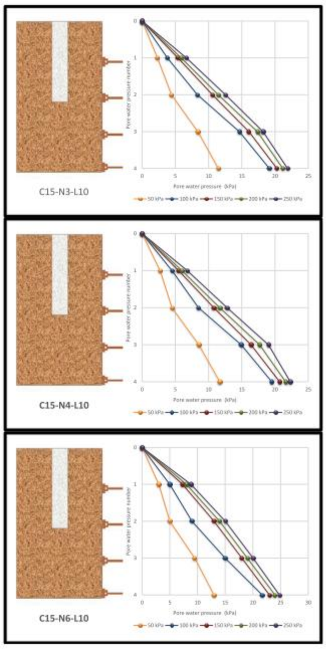

Figure 16. The variation of pore water pressure versus depth of stabilized kaolin clay specimens by length/depth ratio of 0.50.

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Reference

Ahmadi, H., Rahimi, H., and Soroush, A. (2011). Investigation on the Characteristics of Pore Water Flow During CRS Consolidation Test. Geotechnical and Geological Eng., 29:989-997.

Arulrajah A., Abdullah A., Bo M.W., and Bouazza A., (2009). Ground improvement techniques for railway embankments. Ground Improvement., 162(1):3-14.

Arulrajah A., Yaghoubi M., Disfani M.M., Horpibulsuk S., Bo M.W., and Leong M. (2018). Evaluation of fly ash and slag based geopolymers for the improvement of a soft marine clay by deep soil mixing. Soils and Foundations., 58:1358-1370.

ASTM (1982) Standard test method for one-dimensional consolidation properties of soils using controlled-strain loading. ASTM standard D4186-82. In: American Society of Testing Materials, West Conshohocken, p. 04.08:534-538.

Awg Shahminan, D.N.I.A., Rashid, A.S.A., Ridzuan Bunawan, A., Yaacob, H., and Noor, N.M. (2014). Relationship between strength and liquidity index of cement stabilized laterite for subgrade application. Int. J. Soil Sci., 9(1):16-21.

Bouassida, M. and Porbaha, A. (2004a). Ultimate bearing capacity of soft clays reinforced by a group of columns: Application to a deep mixing technique. Soils and Foundations., 44(3):91-101.

Bouassida, M., and Porbaha, A. (2004b). Bearing capacity of foundations resting on soft ground improved by soil cement columns. In: International conference on geotechnical engineering (ICGE 2004), United Arab, p. 173-180.

British Standard 1377. (1990). Methods of test for soils for civil engineering purposes. in: British Standards Institution, London.

Chai, J.C., Miura, N., Kirekawa, T., and Hino, T. (2010). Settlement prediction for soft ground improved by columns. Procee of the ICE-Ground Improvement., 163(2):109-119.

Chai, J. and Pongsivasathit, S. (2010). A method for predicting consolidation settlements of floating column improved clayey subsoil. Frontiers of Architecture and Civil Eng. in China., 4(2):241-251.

Chu J., Bo. M.W., and Arulrajah A. (2009a). Reclamation of a slurry pond in Singapore. Geotechnical Eng. Institution of Civil Eng. (UK)., 162(1):13-20.

Chu J., Bo. M.W., and Arulrajah A. (2009b). Soil improvement works for an offshore land reclamation. Geotechnical Eng. Institution of Civil Eng. (UK)., 162(1):21-32.

Dehghanbanadaki A., Ahmad K., Ali N., Khari M., Alimohammadi P., and Latifi N. (2013). Stabilization of soft soils with deep mixed soil columns-general perspective. Electronic J. Geotechnical Eng., 18B: 295-3062013.

Disfani, M.M., Mohammadinia, A., Arulrajah, A., Horpibulsuk, S., and Leong, M. (2021). Lightly stabilized loose sands with alkali-activated fly ash in deep mixing applications. Int. J. Geomechanics., 21(3):04021011(1-11)

Fang, Z. (2006). Physical and Numerical Modelling of the Soft Soil Ground Improved by Deep Cement Mixing Method. Pao yue-kong library, hong kong, 304p.

Gong X., Tian X., and Hu W. (2015). Simplified method for predicating consolidation settlement of soft ground improved by floating soil-cement column. In: Central South University press and Springer-Verlag. China, p. 2699-2706

Horpibulsuk, S., Chinkulkijniwat, A., Cholaphatsorn, A., Suebsuk, J., and Liu, M.D. (2012). Consolidation behavior of soil cement column improved ground. Com. and Geotechnics., 43:37-50.

Horpibulsuk, S., Miura, N., Koga, H., and Nagaraj, T.S. (2004). Analysis of strength development in deep mixing-A field study. Ground Improvement J., 8(2):59-68.

Horpibulsuk, S., Rachan, R., Suddeepong, A., and Chinkulkijniwat, A. (2011). Strength development In cement admixed Bangkok clay: laboratory and field investigations. Soils and Foundations., 51(2): 239-251.

Ishikura, R., Ochia, H., Yasufuku, N., Omine, K., and Kobayashi, T. (2005). Consolidation and Deformation Properties of Improved Ground with Floating Type Cement-Treated Columns. In: Proceedings of Recent Developments of Geotechnical Engineering in Soft Ground, Japan, p. 322-327

Ishikura, R., Ochia, H., Yasufuku, N., Omine, K., and Kobayashi, T. (2007). Estimation of Settlement of Improved Ground with floating types cement-treated columns. In: International Proceeding of the 4th International on Soft Soil Engineering, Vancouver, Canada, p. 2394-2398.

Ishikura, R., Yasufuku, N., and Brown, M.J. (2016). An estimation method for predicting final consolidation settlement of ground improved by floating soil cement columns. Soils and Foundations., 56 (2):213-227.

(JICE) Japan Institute of Construction Engineering. (1999). Flexible foundation, foundation structure part, design code for flexible box culvert (Chapter 4). San-kai-dou Press Tokyo., 233-248.

Jiang, Z., Ishikura, R., and Yasufuku, N. (2014). Evaluation of settlement behaviors of the improved ground by using floating type cement-treated columns during consolidation. Hair Transplantation: The Art of Micrografting and Minigrafting., 435.

Karastanev, D., Kitazume, M., Miyajima, S., and Ikeda, T. (1997). Bearing capacity of shallow foundation on column type DMM improved ground. In: Proceedings of the International Conference on Oil Mechanics and Foundation Engineering-International Society for Soil Mechanics and Foundation Engineering, AA: Balkema, p. (3):1621-1624.

Kassim K.A. and Clarke B.G. (1999). Constant rate of strain consolidation equipment and procedure for stabilised soils. Geotech Testing J., 22:13-21.

Kassim, K.A., Rashid, A.S.A., Kueh, A.B.H., Yah, C.S., and Siang, L.C. (2016). Criteria of acceptance for constant rate of Strain consolidation test for tropical cohesive soil. Geotechnical and Geological Eng., 1-17.

Kassim, K.A., Rashid, A.S.A., Kueh, A.B.H., Yah, C.S., Siang, L.C., Noor, N.M., and Moayedi, H. (2014). Development of Rapid Consolidation Equipment for Cohesive Soil. Geotechnical and Geological Eng., 33:167-174

Kitazume, M. (1996). Bearing capacity of improved ground with column type DMM. Grouting and deep mixing., 503-508.

Kitazume, M. and Terashi, M. (2002). The deep mixing method principle, design and construction. Coastal Development Institute of Technology, Japan, Balkema.

Labuz, J.F., Theroux, B. (2005). Laboratory calibration of earth pressure cells. Geotehnical testing J., 28(2):188-196

Lee K. (1981). Consolidation with Constant Rate of Deformation. Geotechnique., 31(2):215-229.

Lorenzo, G.A. and Bergado, D.T. (2003). New consolidation equation for soil cement pile improved ground. Canadian Geotechnical J., 40(2):265-275.

Mohammadinia, A., Disfani, M.M., Conomy, D., Horpibulsuk, S. and Darmawan, S. (2019). Utilization of alkali-activated fly ash for construction of deep mixed columns in loose sands. J. Materials in Civil Eng., 31(10):04019233(1-8)

Omine, K., Ochiai, H., and Bolton, M.D. (1999). Homogenization method for numerical analysis of improved ground with cement- treated soil columns. In: Proceedings of the International Conference on Dry Dry Mix Methods for Deep Soil Stabilization. H. Bredenberg, B.B. Broms, and G. Holm. p.161-168.

Özgen, C. (2011). The deformation characteristics of deep mixed columns in soft clayey soils: a model study. Middle East Technical University.

Phetchuay C., Horpibulsuk S., Arulrajah A., Suksiripattanapong C., and Udomchai A. (2016). Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer. Applied Clay Sci., 127-128:134-142.

Porbaha, A. (1998). State of the art in deep mixing technology: part I. Basic concepts and overview. Procee of the Institution Civil Eng-Ground Imp., 2(2):81-92.

Porbaha, A. and Bouassida, M. (2004). Bearing capacity of foundations resting on soft ground improved by soil cement columns. In: International Conference on Geotechnical Engineering, Sharjah, UAE, p. 172-180.

Raftari, M., Rashid, A.S.A., Kassim, K.A., and Moayedi, H. (2014). Evaluation of kaolin slurry properties treated with cement. Measurement: J. the Int. Meas. Confederation., 50(1):222-228.

Rashid, A.S.A., Zainudin, Z., Md Noor, N., and Yaacob, H. (2013). Effect of stabilized laterite on California bearing ratio (CBR) and unconfined compressive strength (UCS). Electronic J. Geotechnical Eng., 18(X):5655-5660.

Rashid, A.A.S, Black, J.A, Mohamad, H., and Mohd Noor, N. (2015a). Behavior of weak soils reinforced with end-bearing soil-cement columns formed by the deep mixing method. Marine Georesources and Geotechnology., 33(6):473-486.

Rashid, A.A.S, Black, J.A., Kueh, A.B.H., and Md Noor, N. (2015b). Behaviour of weak soils reinforced with soil cement columns formed by the deep mixing method: rigid and flexible footings. Measurement: J. the Int. Meas. Confederation., 68:262-279.

Rashid, A.A.S., Kueh, A.B.H., and Mohamad, H. (2017a). Behavior of soft soil improved by floating soil-cement columns. Int. J. Phys. Modelling in Geotechnics, 18(2):95-116

Rashid, A.S.A., Black, J.A., Mohamad, H., Kueh, A.B.H., and Md Noor, N. (2016). Bearing capacity charts of soft soil reinforced by deep mixing. Ground Improvement., 170(1):12-25.

Rashid, A.S.A., Kalatehjari, R., Noor, N.M., Yaacob, H., Moayedi, H., and Sing, L.K. (2014). Relationship between liquidity index and stabilized strength of local subgrade materials in a tropical area. Measurement: J. the Int. Meas. Confederation., 55:231-237.

Rashid, A.S.A., Shahrin, M.I., Horpibulsuk, S., Hezmi, M.A., MohdYunus, N.Z., and Borhamdin, S. (2017b). Development of sustainable masonry units from flood mud soil: Strength and morphology investigations. Cons. and Bldg. Materials., 131:682-689.

Shen, S.L., Wang, Z.F., Sun, W.J., Wang, L.B., and Horpibulsuk, S. (2013). A field trial of horizontal jet grouting using the composite-pipe method in soft deposit of Shanghai. Tunnelling and Underground Space Technol., 35:142-151.

Suksiripattanapong, C., Horpibulsuk, S., Yeanyong, C., and Arulrajah, A. (2021). Evaluation of polyvinyl alcohol and high calcium fly ash based geopolymer for the improvement of soft Bangkok clay. Transportation Geotechnics., 27:100476.

Terashi, M. and Juran, I. (2000). Ground Improvement-state of the art. In: ISRM International Symposium. M. Terashi and I. Juran, Australia p. 2000

Yaghoubi M., Arulrajah A. Disfani M.M., Horpibulsuk S., Bo M. W., and Darmawan S. (2018). Effects of industrial by-product based geopolymers on the strength development of a soft soil. Soils and Foundations., 58:716-728.

Yao, K., Yao, Z., Song. X., Zhang. X., Hu. J., and Pan. X. (2016). Settlement evaluation of soft ground reinforced by deep mixed columns. International J. Pavement Research and Technology., 460-465.

Yin, J.H., and Fang, Z. (2006). Physical modelling of consolidation behaviour of a composite foundation consisting of a cement-mixed soil column and untreated soft marine clay. Geotechnique., 56(1):63-68.