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FEM-based modelling of stabilized fibrous peat by end-bearing cement deep mixing columns

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Abstract. This study aims to simulate the stabilization process of fibrous peat samples using end-bearing Cement Deep Mixing (CDM) columns by three area improvement ratios of 13.1% (TS-2), 19.6% (TS-3) and 26.2% (TS-3). It also focuses on the determination of approximate stress distribution between CDM columns and untreated fibrous peat soil. First, fibrous peat samples were mechanically stabilized using CDM columns of different area improvement ratio. Further, the ultimate bearing capacity of a rectangular foundation rested on the stabilized peat was calculated in stress-controlled condition. Then, this process was simulated via a FEM-based model using Plaxis 3-D foundation and the numerical modelling results were compared with experimental findings. In the numerical modelling stage, the behaviour of fibrous peat was simulated based on hardening soil (HS) model and Mohr-Coulomb (MC) model, while embedded pile element was utilized for CDM columns. The results indicated that in case of untreated peat HS model could predict the behaviour of fibrous peat better than MC model. The comparison between experimental and numerical investigations showed that the stress distribution between soil (S) and CDM columns (C) were 81%C-19%S (TS-2), 83%C-17%S (TS-3) and 89%C-11%S (TS-4), respectively. This implies that when the area improvement ratio is increased, the share of the CDM columns from final load was increased. Finally, the calculated bearing capacity factors were compared with results on the account of empirical design methods.

Keywords: stress distribution; soil cement columns; peat soil; rectangular foundation; numerical modelling

1. Introduction

Dry deep mixing (DDM) using different binders is conventionally used as a means of soil stabilization (e.g., Broms 1979). DDM is classed as a solidification method (Porbaha 1998 and Pongsivasathit *et al.* 2012) and in principal the construction technology of this technique is on basis of thorough mixing of binders with in-situ soft soil using special tools. It is often perceived that once the mixing process is completed and chemical reactions between the materials take place, the developed mixture is more resistant to the induced stresses. There are numerous reports on the effectiveness of this technique for improving the engineering properties of high organic-content soils (e.g., Rathmayer 1996, Porbaha 1998, Bruce 2001, Huat *et al.* 2011).

Construction on peat soils runs the risk of risk of ground failure (Huat *et al.* 2011). Different geotechnical properties of peat soils such as high compressibility and low bearing capacity are notable among other soils. The presence of high organic content in these problematic soils always make the stabilization process harder than normal soils. Moreover, compared to clays, peat is harder to stabilize because of lower pH and lower solid content (Huat *et al.* 2011). Therefore, in peat soils, the method of stabilizations and the needed quantity of binders are significantly different compared to inorganic soils.

There are many proven positive records on the applicability of different binders such as cement, lime, gypsum and their combination for DDM. Table 1 summarizes the applicability of these binders for a range of different soils on the account of experimental investigation on the account of 28-days unconfined compressive strength (EuroSoilStab 2002). In last three decades, many studies aimed to implement numerous computational techniques such as data mining tools and advanced numerical algorithms to solve problems in civil engineering. For example, the application of the techniques are the numerical models for deep mixed column supporting reinforced embankment (Han *et al.* 2005), rigid columns (Zhang *et al.* 2013), deep cement mixing (Boathong *et al.* 2014), stone column-improved soft soil (Labed and Mellas 2016), coastal protection (Abolfathi *et al.* 2016), and water treatment plants (Borzooei *et al.* 2019a, b).

Numerous researchers carried out experimental and numerical investigations on the strength behaviour of improved soil by DDM columns (e.g., Broms 1979, Kitazume *et al.* 1999, 2000, Broms 2001, Tan *et al.* 2002, Bouassida and Porbaha 2004a, b, Horpibulsuk *et al.* 2004, Bouassida *et al.* 2009, Yin and Fang 2010 and Rashid 2011, Jiang *et al.* 2014, Kalantari and Rezazade 2015, Rashid *et al.* 2017, Dao and Hai 2018, Saberian *et al.* 2018, Wonglert *et al.* 2018, Yi *et al.* 2018, Zhou *et al.* 2018). In majority

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Table 1 Application of different binders for DDM (adapted from EuroSoilStab 2002)

Binder	Silt	Clay	Organic soils up to 30%	Peats
Ce	××	×	×	××
Ce + G	×	×	××	××
Ce + FS	××	××	××	×××
Ce + L	××	××	×	-
L+G	××	××	××	-
L+FS	××	×	×	-
Ce + L + G	××	××	××	-

Note: Ce: cement, G: gypsum, FS: furnace slag, L: lime

××× Very good binder in many cases

×× Good in many cases

× Good in some cases

\- Not suitable

of these studies, cement was used as a binder; therefore, in this investigation we focused on *Cement Deep Mixing* (CDM) method as a type of DDM. Table 2 summarizes some of the mentioned researches with details that are similar to the condition of the present study. As can be seen, several factors (e.g., shear strength properties of soil and CDM columns, area improvement ratio, column installation method and loading conditions) that can affect the strength properties of treated ground.

The volume of the soft soil improved by CDM columns plays a key role on the bearing capacity of stabilized soil (CDIT, 2009). To quantify the amount of soft soil replacement the *area improvement ratio* is defined as Eq. (1):

$$\alpha = A_c/A_t \tag{1}$$

where: A_c is the area of the columns and A_t is the total loaded area.

Karstunen (1999) and Bruce and Bruce (2001) stated that commonly a range of 10%-50% for α is used in practice. The load transfer capacity of the applied load to the CDM columns and soft soil depends on different parameters including (a) relative stiffness of the columns to the in-situ soils and (b) the diameter and spacing of the columns (EuroSoilStab 2002). As an assumption, since the vertical strain of CDM columns and soil is approximately equal, the columns must be carrying a greater portion of the stress compared to soft soil (Townsend and Anderson 2004). On this basis, the relationship between the stress in the soft soil and CDM columns is defined in Eq. (2)

$$n = \frac{F_c}{F_s} \tag{2}$$

2here: n = stress distribution ratio; F_c = % load carried by CDM columns and F_s = % load carried by soft soil.

Having said that, a survey of literature shows there is no prior attempt to study the stress distribution between fibrous peat and end-bearing CDM columns. Therefore, the main aim of this study was to experimentally evaluate the ultimate bearing capacity of the stabilized fibrous peat using end-bearing CDM columns. Further, this study also investigated the stress-strain behavior of untreated fibrous peat under a rectangular foundation in stress-controlled condition. The approximate stress distribution between CDM columns and soft peat was evaluated based on FEM using *Plaxis 3D foundation*. The results of the stress-deformation of the physical modelling tests were compared with numerical simulations and some empirical design methods.

2. Experimental procedure

2.1 Sample preparation

Fig. 1 illustrates the particle soil distribution (PSD) curve of the fibrous peat and Table 3 shows the engineering properties of used material in this study. It should be mentioned that, the average undrained shear strength of Pontian area was evaluated by performing several in-situ vane shear tests (VST) in accordance with BS1377: Part 9 (1990).

The experiments were commenced by air-drying the peat passed through 2 mm sieve. Further, natural moisture content of 495% (average of field condition) was added to the peat and then the mixture was poured into a box (Fig.2). To achieve a homogenous texture with the shear strength of about 10 kPa (based on the average results of several VST at the original deposit), the wet peat was consolidated by applying vertical stress of 2 to 15 kPa which was kept constant for four days. This was carried out to accommodate the site conditions. The loading rate was determined based on several pilot tests and the samples were prepared based on Japanese Geotechnical Society Standard (2000). To achieve the required shear strength in acceptable time frame, the consolidation process was carried out in two-way draining condition.

2.2 CDM Column modelling and installation

The required cement dosages for constructing the CDM columns were determined based on the optimum cement amount in UCS tests at constant water content of 495%. Therefore, several UCS tests using different cement dosages were carried out on the stabilized samples to find the

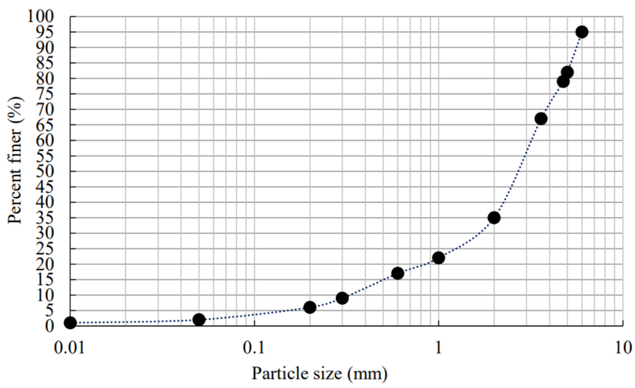


Fig. 1 PSD curves for untreated fibrous peat

Table 2 Summary of studies on stabilized soils by end-bearing and floating CDM columns

Box dimensions (mm)	Foundation dimensions (mm)	Cus (kPa)	Cuc (kPa)	Number of CDM columns	Area ratio (%)	UBC (kPa)	BCF	Reference
End-bearing CDM columns								
400×150×430	149×339	6.9	86.75	6	17.3	80.33	11.64	Rashid (2011) – (TS-1)
400×150×430	149×339	6.4	83.71	9	26.2	90.11	14.08	Rashid (2011) – (TS-2)
400×150×430	149×339	6.4	87.31	9	26.2	96.17	15.03	Rashid (2011) – (TS-3)
400×150×430	149×339	6.3	90.28	12	34.7	107.24	17.02	Rashid (2011) – (TS-4)
500×200×345	75×200	14.1	322	9	18.8	182	12.91	Bouassida & Porbaha (2004) – (TS-1)
500×200×345	75×200	15.7	292	9	18.8	186.7	11.89	Bouassida & Porbaha (2004) – (TS-2)
500×200×345	75×200	9.4	259	9	18.8	132.7	14.12	Bouassida & Porbaha (2004) – (TS-3)
500×200×345	75×200	11	266	9	18.8	152	13.82	Bouassida & Porbaha (2004) – (TS-4)
500×200×345	75×200	12.6	357	9	18.8	181.3	14.39	Bouassida & Porbaha (2004) – (TS-1)
500×200×345	75×200	9.5	347	9	18.8	162.2	17.07	Bouassida & Porbaha (2004) – (TS-5)
900×300×900	300×300	3	425	9	12.6	81	27	Yin and Fang (2010) – (TS-1)
900×170×200	170×150	2.66	29.96	8	22	25	9.4	Omine *et al.* (1999) – (TS-1)
900×170×200	170×150	2.66	29.96	15	42	39.2	14.74	Omine *et al.* (1999) – (TS-2)
900×170×200	170×150	2.66	113.29	8	22	57.9	21.77	Omine *et al.* (1999) – (TS-3)
Floating CDM columns								
400×150×430	149×339	6.1	118.79	12	34.7	61.12	10.01	Rashid *et al.* (2017) – (TS-3)
400×150×430	149×339	6.2	68.98	12	34.7	61.85	9.97	Rashid *et al.* (2017) – (TS-4)
400×150×430	149×339	6.4	121.84	9	26.2	63.56	9.93	Rashid *et al.* (2017) – (TS-5)
400×150×430	149×339	6.4	87.21	9	26.2	67.14	10.49	Rashid *et al.* (2017) – (TS-6)
400×150×430	149×339	6.2	89.62	9	26.2	59.98	9.67	Rashid *et al.* (2017) – (TS-7)

Note: C_{us}: Undrained shear strength of soil and C_{uc}: Undrained shear strength of column, UBC: Ultimate bearing capacity; TS: Test; BCF= (UBC of treated soils) / (undrained shear strength of the soft soil**)**

Fig. 2 Fibrous peat with water content of 495% (before consolidation process)

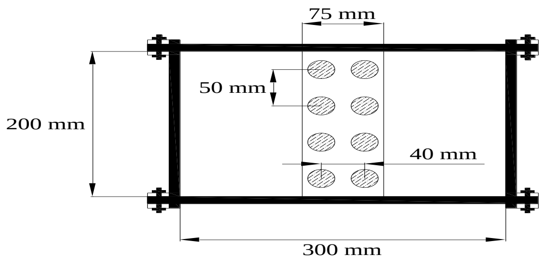


Fig. 4 Dimension of the used box and CDM column arrangement (TS-4)

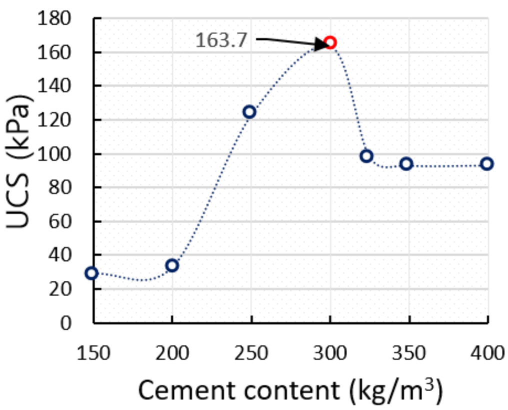


Fig. 3 UCS of CDM columns after 28-day of air curing

optimum cement content. Fig. 3 shows the highest UCS of stabilized peat with cement (CDM columns) after 28-day air curing using 300 kg/m^3 cement dosages. Hence, from Fig. 3 the average UCS of 163.7 kPa was selected for CDM columns.

To evaluate the effects of CDM columns on the UBC of treated peat, four physical modelling tests (TS1-TS4) were fabricated, cured and tested until failure. TS1 represented the unimproved peat; whilst TS2 (4 CDM columns with α = 13.1%), TS3 (6 CDM columns with α = 19.6%) and TS4 (8 CDM columns with α = 26.2%) represented the stabilized tests. In line with the guidelines reported in Sukpunya and Jotisankasa (2016), the CDM columns (diameter of 25 mm) were installed and cured by continuous replacement method.

Table 3 Properties of used material in this experiment

Peat	
Item	Index properties
Water content %	495
Organic content (%)	91
C_c (Untreated)	3
C_α (Untreated - average)	0.065
C_u (kPa)	10
Cement	
Item	Content (%)
Al_2O_3	5.3
CaO	68.6
Fe_2O_3	3.3
MgO	1.1
SiO_2	21.6
SO_3	<0.01

Fig. 4 shows the dimensions of the used box and CDM column arrangement for TS-4. Further, the stabilized peat was cured for 28-day in humidity of approximately 80% before testing was carried out. The curing process of CDM columns was carried out within the soft soil in the tank which was intended to resemble the field conditions more accurate compared to pre-fabricated CDM columns. Similar to the approach used by Omine *et al.* (1999) in order to simulate undrained condition, stress increment of 1 kPa/min was chosen which was applied by a rigid steel rectangular foundation (L=200 mm; W=75 mm and H=20 mm).

3. Numerical modelling

Plaxis 3-D foundation software was used to simulate the stabilization process of untreated peat by CDM columns. This was carried out to evaluate the results of the experimental stress-deformation behaviour of the tested samples. In the stage of numerical modelling, three different materials including fibrous peat soil, CDM columns and rigid foundation were defined.

3.1 Simulation of fibrous peat soil

To simulate the behaviour of the untreated peat, two consecutive models were used: Mohr-Coulomb (MC) and hardening soil (HS). Firstly, MC model was used to model the peat behaviour based on the approach reported by Brinkgreve (2005). Further, the behaviour of peat soil was simulated using HS model which is an elasto-plastic type of hyperbolic model. Table 4 summarizes the details of the input parameters for the simulation process. To determine the input parameters, vane shear tests, UCS tests and consolidation tests were performed on stabilized and undisturbed samples.

3.2 Simulation of the CDM columns and rigid foundation

In the numerical modelling, embedded pile element was

Table 4 Detail of needed parameters for numerical modelling

Items	Source of data	Peat (MC)	Peat (HS)	CDM columns	Rigid foundation
Type of behaviour	-	Undrained	Undrained	--	--
Bulk density (Mg/m3)	Dehghanbanadaki *et al.* (2013)	10	10	10	--
Elastic modulus, E (kPa)	UCS test on CDM columns	500	--	5000	2e8
Poisson's ratio, ν	Tan (2008)	0.15	--	--	0.25
Cohesion, c (kPa)	In situ VST	10	10	--	--
Friction angle, ϕ(o)	Undrained condition	0	--	--	--
Dilatancy angle ψ(o)	Undrained condition	0	--	--	--
Modified compression index-λ^*	Consolidation tests	--	0.35	--	--
Modified swelling index-K^*	Consolidation tests	--	0.059	--	--
Modified creeps index-μ^*	Consolidation tests	--	0	--	--

Note: -- implies that the characteristic is not defined in the software as input

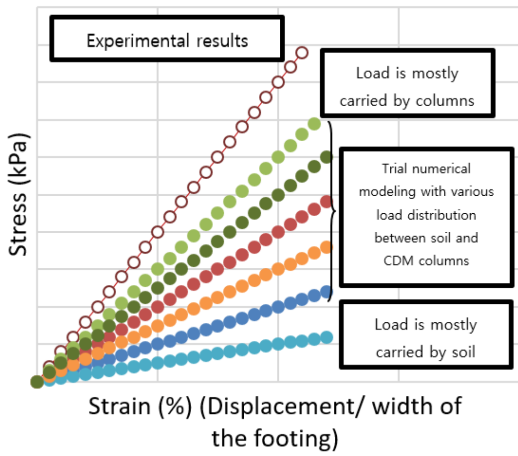


Fig. 5 General trend of stress- strain behaviour of stabilized peat

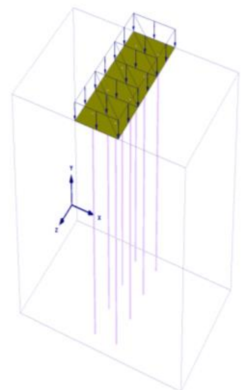


Fig. 6 Numerical simulations of TS-4 (Eight end-bearing CDM columns, α = 26.2%)

used in order to simulate the behaviour of the CDM columns. This embedded pile element is connected to the surrounding soil by means of special interfaces which are skin and tip interfaces and failure of these pile elements is based on their bearing capacity (Septanika 2005). Although the installation effects of the CDM columns was not taken into account in this simulation, this model may effectively be applied in low disturbance situations. In addition, in the course of experiments, during the drilling and pouring the slurry into the holes, no disturbance around CDM columns was observed which is due to the texture of the consolidated peat.

In *Plaxis 3D foundation*, different properties were defined to simulate the CDM columns as embedded pile, including elasticity modulus (E), unit weight (γ), diameter of columns (d) and skin and tip interactions as shown in Table 4. It should be mentioned that, the elasticity modulus of CDM columns was obtained from the results of UCS tests (stress-strain curve) on columns materials. The details of UCS tests and the obtained results are comprehensively discussed in Dehghanbanadaki *et al.* (2013) and in this study the reported UCS results were used. Due to the end bearing condition of CDM columns, the main interaction between the CDM columns and the peat was expected to happen at the tip of embedded pile. Finally, the rectangular foundation in this study was simulated using the input parameters of unit weight (γ) and elasticity modulus (E) as shown in Table 4.

In this study, to find the real stress distribution between the peat and CDM columns, two assumptions were considered based on Brom (2004): (i) it was assumed that due to higher stiffness of the CDM columns compared with peat, the applied stress was carried 100% by the CDM columns and the surrounding soil could not tolerate any load. (ii) It was assumed that the applied stress was divided between the soft soils and CDM columns. To determine this, various trial and error numerical tests using different tip forces of CDM columns were performed and the results of stress-strain behaviour were compared to the experimental findings (see Fig. 5). In order to simulate this, the UBC achieved in the experimental results was divided equally to the number of CMD columns and assigned as tip forces of each CDM column. Finally, the closest curve to the experimental curve was selected as the best approximate of stress distribution as shown in Fig. 5.

3.3 Meshing and loading stages

Based on the recommendation of *Plaxis 3-D foundation* (Scientific Manual, 1998) 15-node wedge element was chosen for 3D meshing process. To obtain more accurate numerical results a fine mesh including approximately 500 triangles was considered. In the software, for loading stage definitions, plastic calculation was considered. To simulate the experimental procedure described in section 2, the stress rate of 1 kPa/min in undrained condition was applied on the strip foundation. In the software, this loading rate on the footing was repeated step by step until failure of the stabilized soil happened. Fig. 6 shows a sample of the numerical simulations of TS-4.

4. Empirical design methods

For determination of UBC of untreated peat, double tangent method (based on Yang *et al*. 2013) was utilized. While in the stabilized tests by CDM columns, two empirical design methods namely simple weighted and Brom's method (Broms, 2004) were used (Eq. (3) and Eq. (4)). It should be noticed that in Eq. (3) the UBC of stabilized soil was derived based on a combination of the bearing capacity of soil in local failure and the creep resistance of the CDM columns. Besides, in both Equations, based on Broms assumptions, the untreated soil and CDM columns are considered to be purely cohesive material and have the same unit weight.

$$q_u = c_{uc}\alpha + (1-\alpha)c_{us} \tag{3}$$

$$q_u = 0.7q_{uc}\alpha + \lambda(1-\alpha)c_{us} \tag{4}$$

Note: λ = 5.5 (Bergado *et al.* (1994)), q_{uc} : UCS of CDM columns (Other parameters are defined in section-1)

5. Results and discussions

5.1 Behaviour of untreated peat

Fig. 5 compares the experimental results of stress-displacement of untreated peat soil with the numerical modelling results. Based on Fig. 7, the results of double tangent method showed the average UBC of 38 kPa, 43 kPa and 57 kPa for experiments, FEM-HS and FEM-MC results respectively (based on TS-1 experimental). In addition, from this figure, the relative difference of 33% between FEM-MC model and experimental results indicated that the MC model overestimated the UBC of unimproved peat while this difference decreased to 11% in the case of FEM-HS. In this study, the stress-displacement behaviour of untreated peat simulated with HS model better match with soft fibrous peat soil compared to MS model. Therefore, in the numerical simulation of stabilized cases, HS model was utilized for the peat.

5.2 Stress – strain curves for stabilized samples

The Stress–strain curves for stabilized samples (TS-2,

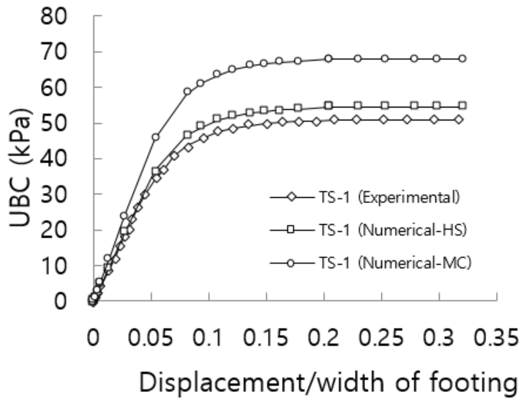


Fig. 7 Vertical stress – (Displacement / width of foundation) – (TS-1)

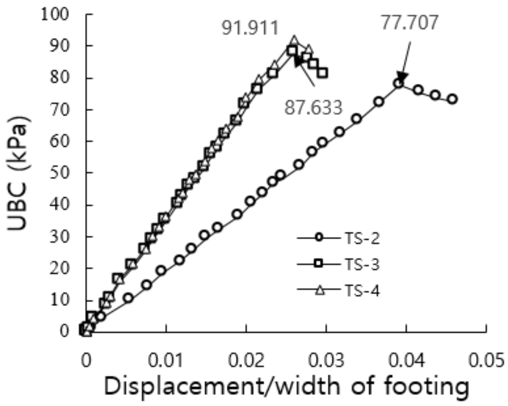


Fig. 8 Vertical stress – (Displacement / width of foundation)

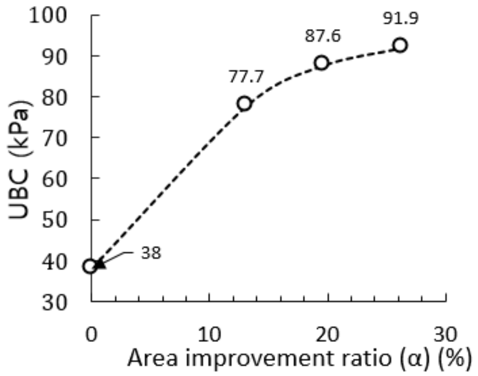


Fig. 9 Effect of α on UBC

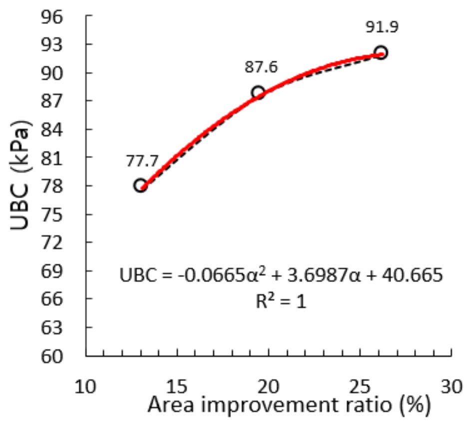


Fig. 10 Derived equation for UBC of treated fibrous peat by end bearing CDM columns

TS-3 and TS-4) are shown in Fig 7. The peak point of Fig. 8 shows the UBC of stabilized samples. As can be seen in all three tests, the trends of the UBC were approximately linear before failure happened (brittle behaviour). Immediately after failure happened, since more stress could not be tolerated, it was observed that the rectangular footing overturned fast. Similar laboratory observations regarding the stress – strain behaviour of the stabilized soils with end – bearing columns were also reported by Yin and Fang (2010).

Fig. 9 depicts the effect of α on UBC of treated peat and compares this UBC with untreated one. Using CDM columns increased the UBC significantly compared to unimproved peat. For example, in the case of TS-4 (8 CDM columns with α = 26.2%), the UBC of stabilized ground increase up to approximately, 240% compared to untreated one with UBC of 38 kPa.

5.3 Derived equation for UBC

In order to determine an experimental equation for the effects of α, the results of TS-2, TS-3 and TS-4 were compared in Fig 10 and the results proposed the Eq. (5) with high regression index of 1. Of course, the validity of this equation is just for the peats and CDM columns with the same range of undrained shear strength of this study.

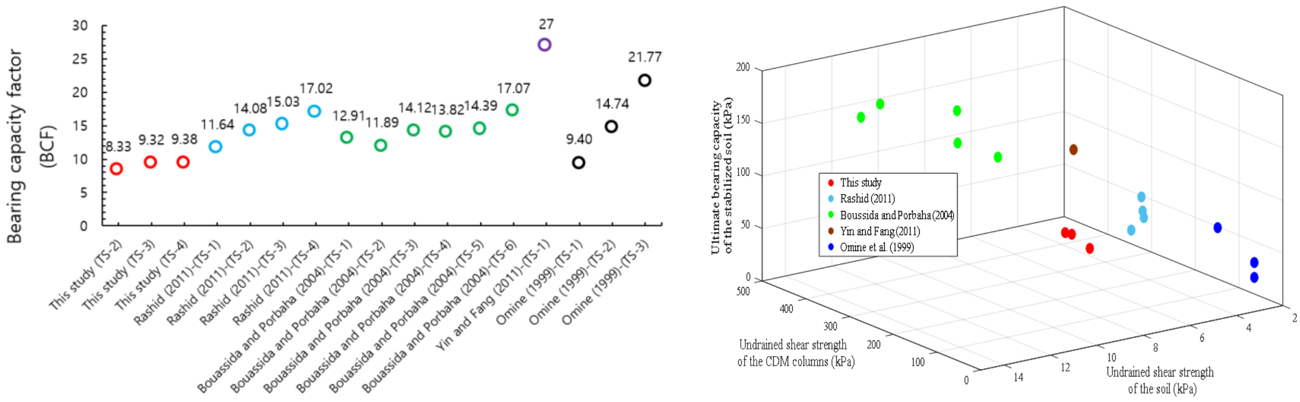
$$UBC = -0.0665\ (\alpha^2) + 3.6978\ (\alpha) + 40.665 \qquad (5)$$

5.4 Comparison with previous experimental tests

Summary of studies on ultimate bearing capacity of small-scaled models treated soil with group of end-bearing CDM columns were presented in introduction section in Table 2. Fig 11(a) compares the calculated BCF of this study with the experimental results (Table 2). For example, the calculated BCF in the study of Yin and Fang (2010), was the highest compared to all since the used soft clay in their study had low c_{us} of 3 kPa while the nine CDM columns had the high c_{uc} of 425 kPa. These high differences in undrained shear strength of clay and columns caused this high BCF. Moreover, in the term of calculated UBC of stabilized tests, Fig 11-b shows the variations of UBC of this study with previous experimental tests. Obviously, the UBC from the experiments of Bouassida and Porbaha (2004) showed the highest values since the constructed CDM columns had the c_{uc} in the ranges of 266 to 357 kPa which is considerably higher compared to the present study. In addition, the UBC values from experimental and numerical methods in this study were also compared with well-known equations of upper and lower bound proposed by Bouassida and Porbaha (2004) and Bouassida (2016). As can be observed from Fig. 12, the experimental results, approximately, were consistent with the upper bound of UBC, while the numerical results in the case of FEM (100%C) overestimated the UBC. One of the possible explanation for this overestimating can be that, in the case of FEM (100%C) when all the loads are carried by just CDM columns, since of higher stiffness of CDM columns compared to soft soil, the numerical predictions of bearing capacity overestimated the analytical results. On the other hand, in the case of FEM(C-S), the trend was consistent analytical methods.

5.5 Determination of stress distribution

Fig. 13(a)-13(c) compare the experimental and numerical results for tests TS-2 to TS-4, respectively. In Fig 10(a), TS2 (FEM-HS) - (100%C) was calculated based on the theory that all the vertical stresses were carried only by



(a) (b)

Fig. 11 Comparison of BCF (a) and UBC (b) of this study to the previous results

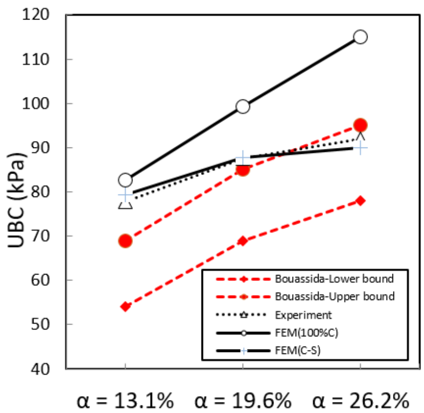
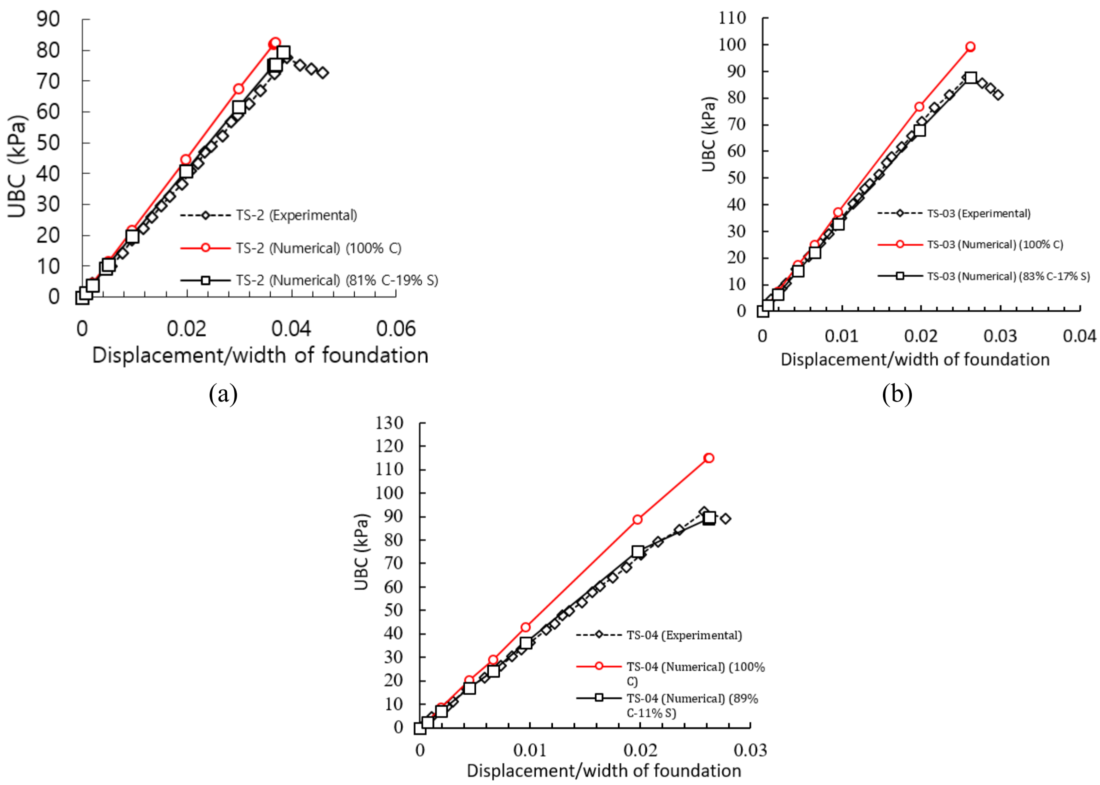


Fig. 12 Comparison of UBC of this study to the well-known methods



(a) (b)

(c)

Fig. 13 Vertical stress – (Displacement / width of foundation) (a) TS-2, (b) TS-3 and (c) TS-4

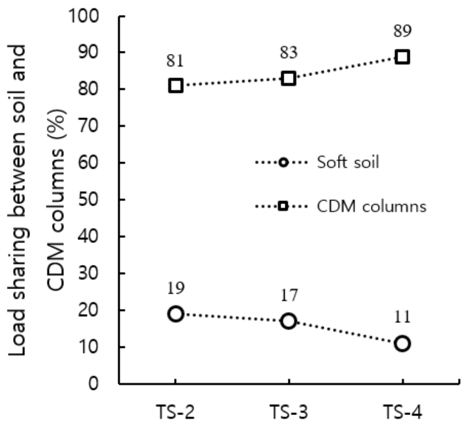
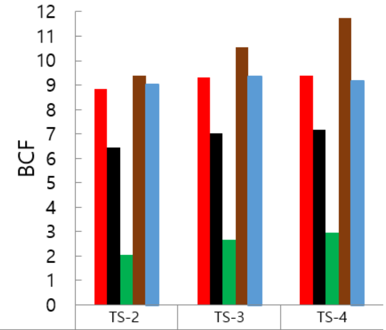
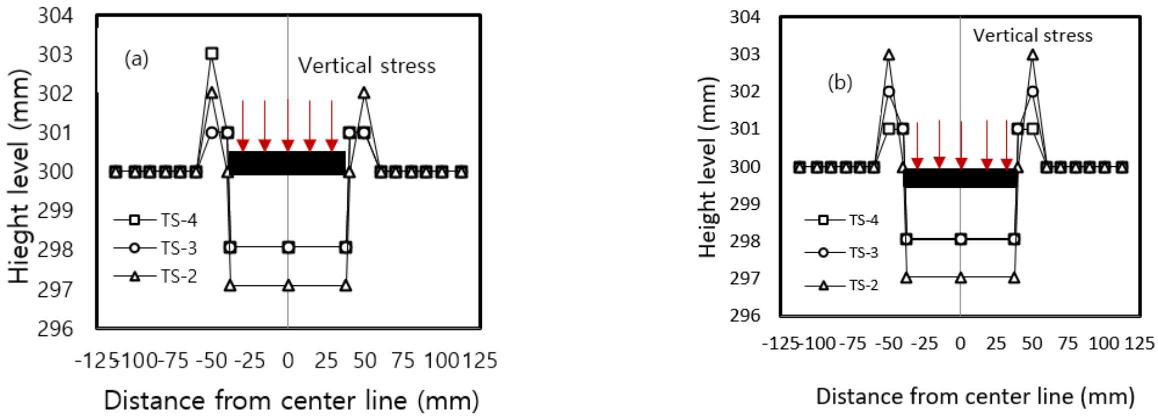


Fig. 14 Stress distribution between soil and CDM columns



	TS-2	TS-3	TS-4
Experimental	8.83	9.32	9.38
Broms	6.44	7.03	7.18
Weighted	2.05	2.67	2.97
FEM-100C	9.38	10.55	11.73
FEM(C-S)	9.01	9.34	9.17

Fig. 15 Comparison of BCF factor to the analytical methods



(a) (b)

Fig. 16 Schematic failure surface (a) Experimental and (b) Numerical

the CDM columns. The calculated UBC for TS2 (FEM-HS)-(100%C) was 82.57 kPa which was 6% more than experimental results. In the cases of TS3 (FEM-HS) - 100%C) and TS4 (FEM-HS) - (100%C), which are shown in Fig 13 (b) and (c), the differences between experimental and numerical UBC reached 13% and 25%, respectively.

Based on Fig 13**.** (a) to Fig. 13 **(**c) by increasing α, the differences between experimental and numerical UBC was increased. For determination of approximate stress distribution between the peat and CDM columns, different trial and errors FEM analysis were performed (see section 3.2). Therefore, the UBC achieved in the experiment was decreased step by step and then divided by the number of the CDM columns. It should be indicated that, it is assumed that the failure load is divided to the CDM columns equally. The results indicated that, in cases of TS2, TS3 and TS4 the probable stress distribution between the soil and CDM columns were 81%C-19%S, 83%C-17%S and 89%C-11%S,

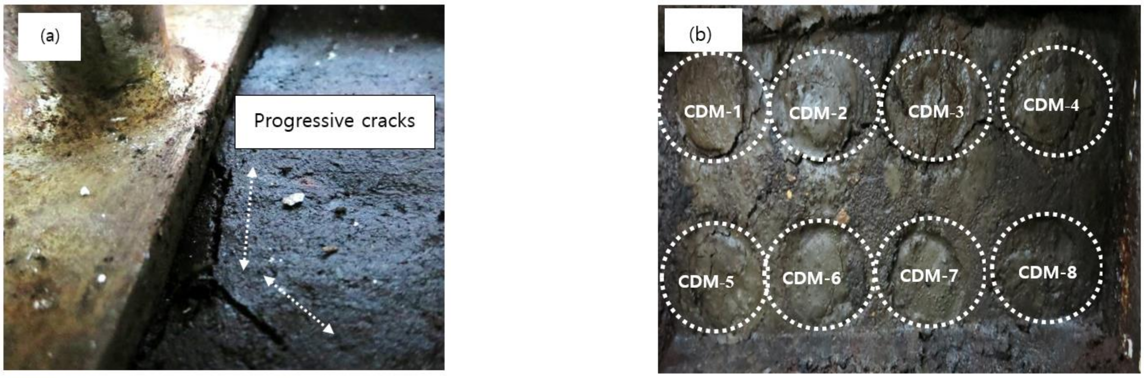


Fig. 17 Failure moment (TS-4): (a) Before failure and (b) After failure

Fig. 18 Sudden failure of foundation

respectively. It could be concluded that, by increasing the number of CDM columns, the share of them from total failure load increased which was due the higher stiffness of the CDM columns compared to the peat. The final results show the real stress distribution between soil and CDM columns in Fig. 14.

It can be estimated that during applying the stress, stress distribution ratio (n) will be increased and the maximum value will be reached at failure moment. Then, this stress distribution ratio showed a progressive reduction after failure moment. The study of Yin and Fang (2010) confirmed this hypothesis. They used earth pressure cells to monitor the variations of the stress distribution between soft clay and CDM column. They reported approximately n (Stress distribution ratio) = 10 for the test with α of 12.6% and c_{uc} of 425 kPa. Of course, the high difference between n of TS2 (4 CDM columns with α = 13.1%) of this study compared to the study of Yin and Fang (2010) is the significant difference in the undrained shear strength of CDM columns.

5.6 Comparison of the results to the analytical methods

In this section, the experimental and numerical BCF of stabilized tests are assessed with different analytical methods. The details of these analytical methods are discussed in section 4. Based on Fig. 15, weighted method underestimated the BCF considerably compared to the all methods. This indicates that the method can be a conservative way to estimate BCF. Yin and Fang (2010) also reported that, weighted method estimate the UBC significantly. On the other hand, in the cases that the failure load is carried just by CDM columns, the derived BCFs were higher than experimental findings. In addition, the experimental BCFs of this study were higher than that of by Broms. Therefore, using simple Broms method can be a logic and conservative way to estimate the UBC of peats with end-bearing CDM columns.

5.7 Numerical and experimental failure pattern

Fig. 16(a) and 16(b) shows the experimental and numerical schematic deformed profile of the treated soil at failure moment. It was predictable that in the numerical modeling the deformed ground should be symmetric while in the case of experimental, a nonsymmetrical heave with average height of around 2 mm was observed around the rectangular foundation. In the experimental tests, before final failure, some small tilting occurred between the right and left corners of the foundation. As can be seen, the average deformability in x-direction was about 60 mm showing that there was no boundary effect in calculation of UBC.

For example, failure moment of TS-4 in (a) Before failure and (b) after failure is illustrated in Fig 17(a) and 17(b). It was interesting that in all tests (TS-2 to TS-4), the failure procedure was approximately the same. In these tests, just 1 CDM column was completely failed (shear failure of the column) and after that the foundation overturned suddenly (Fig 18) and the rest of CDM columns were kept sound. In addition, the location of failed CDM columns were not the same in the tests. It is noted that, these dissimilarities of failure location are because of difference in load distribution between soft peat and CDM columns. It is believed that several factors such as configuration of the CDM columns, engineering properties of the basic soil and CDM columns, loading condition and even installation procedure, can affect the failure patterns. As a comparison to previous work, the failure pattern of the CDM columns of this study is completely consistent with Yin and Fang (2010).

6. Conclusions

The present work deals with a novel experimental and numerical investigation to determine the stress distribution between soft fibrous peat and end-bearing cement deep mixing (CDM) columns. Firstly, the ultimate bearing capacity (UBC) of the stabilized peat by CDM columns using three area improvement ratios of α = 13.1%, α = 19.6% and α = 26.2% were determined in undrained conditions. This stabilization process was simulated and then compared by numerical approaches using finite element method (FEM) based program, *Plaxis 3-D foundation*. In the numerical modelling, two consecutive models namely, Mohr-Coulomb (MC) and hardening soil (HS) model were considered for the peat while the CDM columns were simulated as embedded pile elements. Finally, a comprehensive comparison of UBC was made with empirical design methods. The numerical modelling results showed that in the case of untreated peat, the MC model overestimated UBC with relative differences of 33% while HS model simulated better with acceptable relative differences of 11%. After comparison between numerical and experimental results, the approximate load share of the soil and the CDM columns in cases of TS2 (α = 13.1%), TS3 (α = 19.6%) and TS4 (α = 26.2%) were determined as 81%C-19%S, 83%C-17%S and 89%C-11%S, respectively. Finally, it was revealed that, simple Broms method can be a conservative way to estimate the UBC of peats with end-bearing CDM columns while weighted method significantly underestimated the UBC.

References

Abolfathi, S., Yeganeh-Bakhtiary, A., Hamze-Ziabari, S.M. and Borzooei, S. (2016), "Wave run up prediction using M5′ model tree algorithm", *Ocean Eng*., **112**, 76-81. https://doi.org/10.1016/j.oceaneng.2015.12.016.

Alwi A. (2008), "Ground improvement on Malaysian peat soils using stabilized peat-column techniques", Ph.D. Thesis, University Malaya, Kuala Lumpur, Malaysia.

Babasaki, R. (1996), "Factors influencing the strength of improved soil", *Proceedings of the Symposium on Cement-Treated Soil*.

Bergado, D.T., Anderson, L.R., Miura, N. and Balasubramaniam, A.S. (1994), *Lime/Cement Deep Mixing Method* in *Improvement Techniques of Soft Ground in Subsiding and Lowland Environments*, A.A.Balkelma, Rotterdam, The Netherlands. 99-130.

Boathong, P., Jamsawang, P. and Mairaing, W. (2014), "Lateral movement of slope stabilized with DCM column rows", *Electron. J. Geotech. Eng*., **19**, 1647-1664.

Borzooei, S., Teegavarapu, R., Abolfathi, S., Amerlinck, Y., Nopens, I. and Zanetti, M.C. (2019a), "Data mining application in assessment of weather-based influent scenarios for a WWTP: Getting the most out of plant historical data", *Water Air Soil Pollut*., **230**(1), 5. https://doi.org/10.1007/s11270-018-4053-1.

Borzooei, S., Amerlinck, Y., Abolfathi, S., Panepinto, D., Nopens, I., Lorenzi, E., Meucci, L. and Zanetti, M.C. (2019b), "Data scarcity in modelling and simulation of a large-scale WWTP: Stop sign or a challenge", *J. Water Process Eng*., **28**, 10-20. https://doi.org/10.1016/j.jwpe.2018.12.010.

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 Found*., **44**(3), 91-101. https://doi.org/10.3208/sandf.44.3_91.

Bouassida, M. and Porbaha, A. (2004), "Bearing capacity of foundations resting on soft ground improved by soil cement columns", *Proceedings of the International Conference on Geotechnical Engineering (ICGE 2004)*, Hammamet, Tunisia, March.

Bouassida, M., Jelali, B. and Porbaha, A. (2009), "Limit analysis of rigid foundations on floating columns", *Int. J. Geomech*., **9**(3), 89-101. https://doi.org/10.1061/(ASCE)1532-3641(2009)9:3(89).

British Standard Institution BS (1990), "Methods of test for soils for civil engineering purposes", British Standard Institution, London, U.K.

Bouassida, M. (2016) "Rational design of foundations on soil reinforced by columns", *Innov. Infrastruct. Solut*., **1**(1), 38. https://doi.org/10.1007/s41062-016-0038-3.

Broms, B.B. (2001), "Discussion-Centrifuge model tests on failure envelope of column type deep mixing method improved ground", *Soils Found*., **41**(4), 103-107. https://doi.org/10.3208/sandf.40.4_43.

Broms, B.B. and Boman, P. (1979), "Stabilisation of soil with lime columns", *Ground Eng*., **12**(4), 23-32.

Broms, B.B. (2004), *Lime and Lime/Cement Columns* in *Ground Improvement*, Spon Press, New York, U.S.A., 252-330.

Bruce, D.A. and Bruce, M.E. (2001), "Practitioner's guide to the deep mixing method", *Proc. Inst. Civ. Eng. Ground Improv*., **5**(3), 95-100. https://doi.org/10.1680/grim.2001.5.3.95.

CDIT (Coastal Development Institute of Technology) (2002), *The Deep Mixing Method – Principle, Design and Construction*, Balkelma, Rotterdam, The Netherlands.

Dao, D.H. and Hai, N.M. (2018), "Lateral loading test results on single and groups of soil-cement columns", *Proceedings of the International Foundation Congress and Equipment Expo 2018,* Orlando, Florida, U.S.A., March.

Dehghanbanadaki, A., Ahmad, K. and Ali, N. (2013), "Influence of natural fillers on shear strength of cement treated peat", *Građevinar*, **65**(7), 633-640.

Dehghanbanadaki, A., Sotode, M., Keshtkarbanaeemoghadam, A. and Golpazir, I (2018), "Prediction of geotechnical properties of treated fibrous peat by artificial neural networks", *Bull. Eng. Geol. Environ*., **8**(3), 1345-1358. https://doi.org/10.1007/s10064-017-1213-2.

Duraisamy, Y., Huat, B. and Muniandy, R. (2009), "Compressibility behavior of fibrous peat reinforced with cement columns", *Geotech. Geol. Eng*., **27**, 619-629. https://doi.org/10.1007/s10706-009-9262-3.

Enami, A. and Hibino, S. (1991), "Improvement of foundation ground using a deep mixing blender with free blades", *J. Jap. Soc. Soil Mech. Found. Eng*., **39**(10), 37-42.

EuroSoilStab. (2002), "Development of design and construction methods to stabilise soft organic soils design guide soft soil stabilisation", CT97-0351. Project No. BE 96-3177, Industrial & Materials Technologies Programme (Brite-EuRam III), European Commission.

Han, J., Huang, J. and Porbaha, A. (2005) "2D numerical modeling of a constructed geosynthetic-reinforced embankment over deep mixed columns", *Proceedings of the Geo-Frontiers 2005*, Austin, Texas, U.S.A., January.

Han, J., Zhou, H.T. and Ye, F. (2002), "State-of-practice review of deep soil mixing techniques in China", *Transport. Res. Rec*. **1808**(1), 49-57. https://doi.org/10.3141%2F1808-06.

Hebib, S. and Farrell, E.R. (2003), "Some experiences on the stabilization of Irish peats", *Can. Geotech. J*., **40**(1), 107-120. https://doi.org/10.1139/T02-091.

Hobbs, N. (1986), "Mire morphology and the properties and behaviors of some British and foreign peats", *Quart. J. Eng. Geol*., **19**(1), 7-80. https://doi.org/10.1144/GSL.QJEG.1986.019.01.02.

Hernandez, F. and Tabbaa, A. (2009), "Effectiveness of different binders in stabilization of organic soils", *Proceedings of the*

International Symposium on Deep Mixing and Admixture Stabilization, Okinawa, Japan, May.
Horpibulsuk, S., Miura, N., Koga, H. and Nagaraj, T.S. (2004), "Analysis of strength development in deep mixing: a field study", *Proc. Inst. Civ. Eng. Ground Improv.*, **8**(2), 59-68. https://doi.org/10.1680/grim.2004.8.2.59.
Huat, B.B.K. (2002), "Some mechanical properties of tropical peat and Organic soil", *Proceedings of the 2nd World Engineering Congress*, Sarawak, Malaysia.
Huat, B.B.K., Kazemian, S., Prasad, A. and Barghchi, M. (2011), "A study of the compressibility behavior of peat stabilized by DMM. Model and FE analysis", *Int. J. Phys. Sci.*, **6**(1), 196-204. https://doi.org/10.5897/SRE10.790.
Japanese Geotechnical Society Standard. (2000), *Practice for Making and Curing Stabilized Soil Specimens without Compaction (JGS 0821-2000)*.
Yin, J.H. and Fang, Z. (2010), "Physical modeling of a footing on soft soil ground with deep cement mixed soil columns under vertical loading", *Mar. Georesour. Geotechnol.*, **28**(2), 173-188. https://doi.org/10.1080/10641191003780872.
Jiang, Y., Han, J. and Zheng, G. (2014), "Influence of column yielding on degree of consolidation of soft foundations improved by deep mixed columns", *Geomech. Eng.*, **6**(2), 173-194. http://dx.doi.org/10.12989/gae.2014.6.2.173.
Kalantari, B. and Rezazade, R.K. (2015), "Compressibility behaviour of peat reinforced with precast stabilized peat columns and FEM analysis", *Geomech. Eng.*, **9**(4), 415-426. http://dx.doi.org/10.12989/gae.2015.9.4.415.
Karstunen, M. (1999), "Alternative ways of modelling embankments on deep-stabilized soil", *Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization*, Stockholm, Sweden, October.
Kazemian, S., Huat, B., Prasad, A. and Barghchi, M. (2011), "Study of peat media on stabilization of peat by traditional binders", *Int. J. Phys. Sci.*, **6**(3), 476-481. http://doi.org/10.5897/IJPS10.478.
Kitazume, M., Yamamoto, M. and Udaka, Y. (1999), *Vertical Bearing Capacity of Column Type DMM Ground with Low Improvement Ratios* in *Dry Mixing Methods for Deep Soil Stabilization*, Balkema, Rotterdam, The Netherlands, 245-250.
Kitazume, M and Okano, K. and Miyajima, S. (2000), "Centrifuge model tests on failure envelope of column type deep mixing method improved ground", *Soils Found.*, **40**(4), 43-55. http://doi.org/10.3208/sandf.40.4_43.
Labed, M. and Mellas, M. (2016), "Stability of geosynthetic reinforced embankments over stone column-improved soft soil", *J. Appl. Eng. Sci. Technol.*, **2**(2), 65-74.
Omine, K., Ochiai, H. and Bolton, M.D. (1999), "Homogenization method for numerical analysis of improved ground with cement treated soil columns", *Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization*, Stockholm, Sweden, October.
Pathivada S. (2005), "Effects of water Cement ratio on deep mixing treated expansive clay characteristics", M.Sc. Thesis, University of Texas at Arlington, Arlington, Texas, U.S.A.
Pongsivasathit, S., Chai, J.C. and Ding, W.Q. (2012), "Consolidation settlement of floating column improved soft clayey deposit", *Proc. Inst. Civ. Eng. Ground. Improv.*, **166**(1), 44-58. https://doi.org/10.1680/grim.11.00028.
Porbaha, A. (1998), "State of the art in deep mixing technology: part I. basic concepts and overview", *Proc. Inst. Civ. Eng. Ground. Improv.*, **2**(2), 81-92. https://doi.org/10.1680/gi.1998.020204.
Brinkgreve, R.B.J. and Vermeer, P.A. (1998), *Plaxis: Finite Element Code for soil and Rock Analysi*s, Balkema, Rotterdam, The Netherlands.
PLAXIS (1998), *PLAXIS 3D FOUNDATION Scientific Manual 1998*. Version 2.
Rashid, A. (2011), "Behavior of weak soils reinforced with soil columns formed by deep mixing method", Ph.D. Thesis, University of Sheffield, Sheffield, England, U.K.
Rashid, A.S.A., Kueh, A.B.H. and Mohamad, H. (2017), "Behaviour of soft soil improved by floating soil-cement columns", *Int. J. Phys. Modell. Geotech.*, **18**(2), 95-116. https://doi.org/10.1680/jphmg.15.00041.
Rathmayer, H. (1996), "Deep mixing methods for soft soil improvement in the Nordic countries", *Proceedings the 2nd International Conference on Ground Improvement Geosystems, Grouting and Deep Mixing*, Tokyom Japan, May.
Saberian, M., Moradi, M., Vali, R. and Li, J. (2018), "Stabilized marine and desert sands with deep mixing of cement and sodium bentonite", *Geomech. Eng.*, **14**(6), 553-562. https://doi.org/10.12989/gae.2018.14.6.553.
Sobhan, K., Ramirez, J. and Reddy, D. (2012), "Cement stabilization of highly organic subgrade soil for controlling secondary compression settlement", *Transport. Res. Rec.*, **2310**(1), 103-112. https://doi.org/10.3141%2F2310-11.
Sukpunya, A. and Jotisankasa, A. (2016), "Large simple shear testing of soft Bangkok clay stabilized with soil-cement-columns and its application", *Soils Found.*, **56**(4), 640-651. https://doi.org/10.1016/j.sandf.2016.07.005.
Tan, T.S., Goh, T.L. and Yong, K.Y. (2002), "Properties of Singapore marine clays improved by cement mixing", *Geotech. Test. J.*, **25**(4), 422-433. https://doi.org/10.1520/GTJ11295J.
Townsend, F.C. and Anderson, J. (2004), "A compendium of ground modification techniques", Florida Department of Transportation.
Von Post, L. (1922), "SGU peat inventory and some preliminary results", *Svenska Mosskulturfoereningens Tidskrift*, **36**, 1-37.
Yang, G.H., Luo, Y.D., Zhang, Y.C. and Wang, E.Q. (2013), "Application of the tangent modulus method in nonlinear settlement analysis of sand foundation", *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, France, September.
Wahyunto, D.A. and Fahmuddin, A. (2010), "Distribution, properties, and carbon stock of Indonesian peatland", *Proceedings of the International Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in Asian Countries*, Bogor, Indonesia, September.
Wong, L., Roslan, H. and Faisal, H. (2008), "Behavior of stabilized peat soils in unconfined compression tests", *Am. J. Eng. Appl. Sci.*, **1**(4), 274-279.
Wonglert, A., Jongpradist, P., Jamsawang, P. and Larsson, S. (2018), "Bearing capacity and failure behaviors of floating stiffened deep cement mixing columns under axial load", *Soils Found.*, **58**(2), 446-461. https://doi.org/10.1016/j.sandf.2018.02.012.
Yi, Y., Liu, S. and Puppala, A.J. (2018), "Bearing capacity of composite foundation consisting of T-shaped soil-cement column and soft clay", *Transport. Geotech.*, **15**, 47-56. https://doi.org/10.1016/j.trgeo.2018.04.003.
Zheng, G., Diao, Y., Li, S. and Han, J. (2013), "Stability failure modes of rigid column-supported embankments", *Proceedings of the Geo-Congress 2013: Stability and Performance of Slopes and Embankments III*, San Diego, California, U.S.A., March.
Zhou, H.Z., Zheng, G., Yu, X., Zhang, T.Q. and Liu, J.J. (2018), "Bearing capacity and failure mechanism of ground improved by deep mixed columns", *J. Zhejiang Univ. Sci. A*, **19**(4), 266-276. https://doi.org/10.1631/jzus.A1700517.

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Notations

UBC	Ultimate bearing capacity
TS	Test
CDM	Cement deep mixing
FEM	Finite element modeling
DDN	Dry deep mixing
α	Area improvement ratio
Ac	Area of the columns
At	The total loaded area
n	Stress distribution ratio
F_c	% load carried by CDM columns
F_s	% load carried by soft soil
Ce	cement
G	gypsum
FS	Furnace slag
L	Lime
C_{us}	Undrained shear strength of soil
C_{uc}	Undrained shear strength of column
BCF	Bearing capacity factor
MC	Mohr-Coulomb
HS	Hardening