

Technical Paper

Bearing capacity optimization of T-shaped soil-cement column-improved soft ground under soft fill

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Abstract

During dredging activities, a large amount of dredged clay slurry or lump is produced. A dumping site composed of soft clay near the water body is often used to deposit dredged soft fill. Soil-cement columns are commonly employed to treat the soft ground for this application. Under soft fill, failure of soft clay dominates the behaviour of composite ground. Hence, a soil-cement slab is needed to form a load transfer platform above the columns, which is costly. As an alternative, the use of T-shaped column with an enlarged column cap is proposed. In this study, the responses of composite ground with T-shaped column are measured experimentally, which are used to calibrate a numerical model. The results of numerical parametric analyses show that the implementation of T-shaped column under soft fill can change the governing failure mode into column failure, once the diameter of column cap exceeds a certain value, after which the improvement efficiency is the same between T-shaped column and column-slab system. The height of column cap results in negligible difference in bearing capacity, and a minimum value of 0.3 m is suggested for use in design to avoid punching failure.

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Keywords: Composite ground; T-shaped column; Soft fill; Bearing capacity; Optimization

1. Introduction

As a low-cost but efficient transportation mode, water transportation can influence the economy of a nation significantly. The required water depth increases over time, since the demand in the use of waterways becomes increasingly higher due to the development of massive vessels. Regular maintenance of waterways is hence required. Dredging is carried out in different water bodies, such as rivers, lakes, and harbors, on a regular basis to improve the water feature, deepen the channel, enhance the ship

navigation character, and minimize the flood potential. Sediments and debris are excavated from the bottom of waterways using either cutter suction dredger or grab (clamshell) dredger. Cutter suction dredger can produce clay slurry with a water content of 2–4 times its liquid limit (Kitazume and Satoh, 2003, 2005), whilst clamshell dredger can produce grabbed clay lump with a water content that is well below its liquid limit (Leung et al., 2001; Karthikeyan et al., 2004). Both clay slurry and lump have high compressibility, low hydraulic conductivity, and low shear strength (Burgos et al., 2007; Federico et al., 2015; Wang et al., 2017; Ni et al., 2019a). It is often hard and uneconomic to dispose these excavated materials to landfills. Hence, dredged materials are commonly deposited on the bank that is in close proximity to the water body. The

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authorities need to secure a dumping site, within which dredged materials are filled to an elevation that is as high as possible, taking into consideration the cost.

A dumping site is near the water body, and as such soft clay is commonly encountered. The bearing capacity of soft clay is usually insufficient to implement the depositing activity of dredged materials to a high elevation. Ground improvement with soil-cement columns, installed by deep mixing (Bruce, 2001; Shen et al., 2008; Chai and Carter, 2011; Shen et al., 2017), is a common method to increase the bearing capacity for a dumping site. Control structures, such as dams or dikes, are constructed around the perimeter of the dumping site as illustrated in Fig. 1, within which dredged materials can be deposited.

Conventionally, soil-cement columns are installed to form a composite ground under either rigid footing or embankment fill (Wu, 2000; Gong, 2007). For these common applications, the failure mode of composite ground is governed by column failure (Ni et al., 2019b). Soil arching can be mobilized between soil and column due to the occurrence of differential settlement in embankment fill above the composite ground, triggering load transfer and improving the bearing capacity (Bergado and Lorenzo, 2002; Horpibulsuk et al., 2012; Rowe and Liu, 2015; Yi et al., 2016; Chai et al., 2017; King et al., 2017). At present, soil arching models are only developed to characterize the response of soil-cement column-improved ground under embankment fill (Iglesia et al., 2014; Han et al., 2017; Rui et al., 2018; Zhang et al., 2018; Zhuang and Wang, 2018). At a dumping site for dredging activities, the composite ground with conventional soil-cement column is used under soft fill as illustrated in Fig. 1a. The magnitude of differential settlement above the composite ground becomes too high to form the soil arch, leading to failure of the surrounding soil easily (Ni et al., 2019b).

Therefore, in a dumping site, alternative measures are proposed to make full use of column strength prior to the occurrence of soil failure. One technique is to implement a load transfer platform, e.g. column-slab system, between the composite ground with conventional soil-cement column and the soft fill material as shown in Fig. 1b. The column-slab system is usually constructed

above the composite ground with a thickness of approximately 1 m using the shallow mixing method (Shen et al., 2001), which needs to cover the whole soft soil region, leading to a waste of cementitious materials. To reduce the amount of binders, the use of T-shaped column with an enlarged column cap is proposed to improve the performance of composite ground under embankment fill (Liu et al., 2012; Yi et al., 2016; Yi et al., 2017; Phutthananon et al., 2018; Wijerathna, 2018; Yi et al., 2018; Yi et al., 2019; Phutthananon et al., 2020a; Phutthananon et al., 2020b; Zhou et al., 2020), but there is no study on the behaviour of T-shaped column-improved ground under soft fill. Due to the difference in failure mode of composite ground under embankment fill and soft fill, it is important to study the bearing capacity behaviour of T-shaped column-improved ground under soft fill as depicted in Fig. 1c, which can potentially result in the equivalent improvement efficiency compared to the implementation of load transfer platform.

In this study, controlled model-scale laboratory tests are conducted under the 1-g condition to simulate the performance of composite ground with T-shaped column for the calibration purpose. Upon the successful reproduction of experimental measurements for T-shaped column-improved ground, a numerical parametric investigation is performed to assess the influence of input parameters on the bearing capacity behaviour of composite ground under soft fill, including the undrained shear strength of untreated soil and soft fill, column strength, column spacing, area replacement ratio (area ratio between the column and the untreated ground) of column and column cap, and diameter and height of column cap.

2. Physical modelling

2.1. Test chamber

In the laboratory, controlled model-scale tests are carried out to reproduce the bearing capacity behaviour of composite ground with T-shaped column. A sand cushion, on which surcharge pressure can be imposed, is employed to reproduce the effect of overburden as presented in

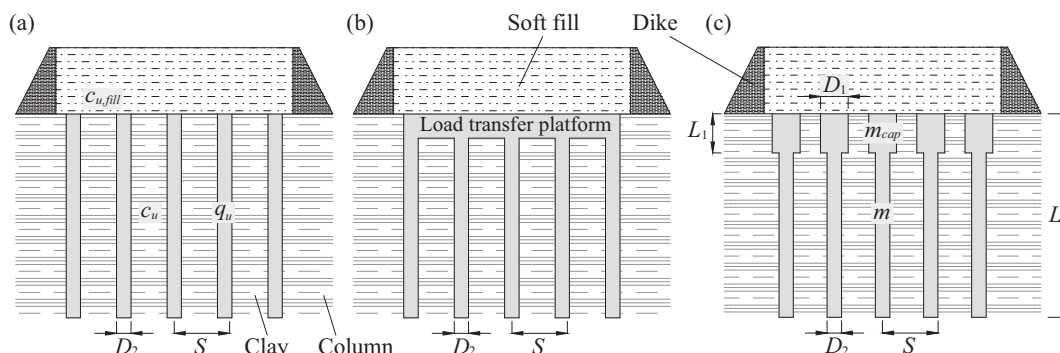


Fig. 1. Schematics of composite ground with soil-cement columns under soft fill: (a) conventional column (Ni et al., 2019b), (b) conventional column with load transfer platform, and (c) T-shaped column with enlarged column cap.

Fig. 2. Ni et al. (2019b) indicated that it is hard to model the case of soft fill above a composite ground directly, due to the difficulty in the application of surcharge and the sealing problem. It should be noted that the behaviour of composite ground with conventional soil-cement column under embankment fill (sand cushion in this case) is controlled by column failure, whereas the response of column-improved composite ground under soft fill is governed by soil failure (Ni et al., 2019b). Despite that the failure mode differs, the present model-scale test for T-shaped column-improved ground is conducted with caution, and is mainly used for the calibration purpose of the numerical model only.

All dimensions are reduced by a factor of 1:10 considering the cost and the ease of implementation. It is well recognized that some laws of similitude should be applied to scale down the model, which can reproduce the prototype-scale behavior with much less experimental efforts. Normally, the geometry of the problem can be well described, but the stress level in the ground cannot be simulated correctly under the 1-g condition. The reliability of model-scale test is generally satisfactory for kinematic problems. In this study, the failure pattern in the ground or the T-shaped soil-cement column is primarily concerned, which is not very much stress-dependent (Phutthananon et al., 2018; Phutthananon et al., 2020a; Phutthananon et al., 2020b). The elevation of embankment fill is not imposed directly; instead, an actuator is employed to exert surcharge on the loading plate. It should be emphasized that the correct prototype stress field is not modelled, which is a limitation of the current model-scale test. The sand cushion is confined within a PVC pipe, and silicone grease is applied on the inside surface of the pipe to reduce the friction mobilized at the sand-pipe interface. The cush-

ion has a thickness of 20 cm, which was found by Yi et al. (2016) to be a proper choice for reproducing differential settlement in the embankment fill. The settlement feature of soft fill could differ, and is investigated numerically once the finite element model is calibrated.

The T-shaped column has a diameter of $D_2 = 5$ cm and a length of 60 cm, and the column cap has a diameter of $D_1 = 11$ cm and a height of $L_1 = 10$ cm; whereas the conventional column has a constant diameter of 5 cm and a length of 60 cm. The thickness of soft clay equals to the total column length, which is to reproduce the behaviour of fully penetrating column (Chai and Carter, 2011). With a scale factor of 10, the modelled T-shaped column corresponds to have a column diameter of $D_2 = 0.5$ m, a length of 6 m, a column cap diameter of $D_1 = 1.1$ m, and a column cap height of $H_1 = 1$ m; whilst the modelled conventional column has a diameter of 0.5 m and a length of 6 m. In practice, the spacing (S) between columns can vary from 1.0 m to 2.2 m (Liu et al., 2012; Ye et al., 2012), and the area replacement ratio falls within 8–20% (Yi et al., 2016). In this study, a composite ground with a single column is simulated due to the limitation in the testing facility. The diameter of PVC pipe is 16 cm. Therefore, for T-shaped column, the area replacement ratio for column and column cap is calculated roughly as $m = 10\%$ and $m_{cap} = 47\%$, respectively. For conventional column, the area replacement ratio is derived as $m = 10\%$. It should be noted that the area replacement ratio for column falls within the commonly used range in practice, but the value for column cap can be much larger. The purpose of this study is to optimize the geometry of column cap, such that the use of T-shaped column can produce sufficient improvement efficiency compared to the use of load transfer platform (slab). Below the soft clay, a 5 cm thick sand

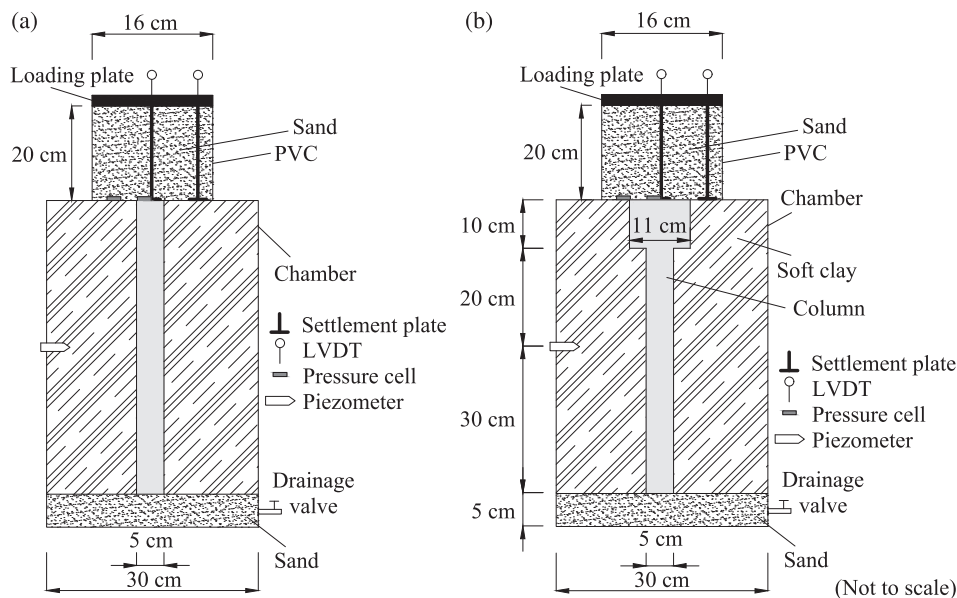


Fig. 2. Test setup of composite ground under a sand cushion of 20 cm: (a) conventional column (after Ni et al. (2019b)), and (b) T-shaped column.

layer is placed, and there is a drainage valve in the sand layer. Silicone grease is also applied at the lateral boundaries of the test chamber to minimize the boundary effect.

2.2. Materials

Within the test chamber, a T-shaped column is employed to treat the soft clay layer to form a composite ground. A drainage layer using poorly graded sand ($d_{10} = 0.15$ mm, $d_{30} = 0.2$ mm, $d_{60} = 0.4$ mm, $C_u = 2.67$, and $C_c = 0.67$) is firstly poured in the test chamber. The drainage layer is then subjected to an overburden pressure of 96 kPa to allow the full consolidation settlement. The soft clay has a plastic limit of 33%, a liquid limit of 74%, and a plasticity index of 41%. The soft clay is dried and filtered through a 2 mm sieve, after which water is added to produce the mixture with a water content of 110%, exceeding the liquid limit of 74% by approximately 1.5 times. The clay mixture is then added in the container to allow pre-consolidation under a surcharge of 24 kPa, during which drainage is allowed in the bottom of the chamber. The pre-consolidation stage is finished by observing the readings from the piezometer (less than 4 kPa) installed in the middle of the chamber as shown in Fig. 2. The water content of soft clay after pre-consolidation is around 73%. The undrained shear strength (c_u) of soft clay is measured by a miniature vane shear device. Higher c_u values are obtained as 11 kPa and 9 kPa near the top and the bottom boundaries, respectively, and the value of 7 kPa is measured in the middle of the container. This is anticipated since the drainage distance is shorter at the top and bottom boundaries.

In this investigation, a hole in the soft clay is drilled with an auger. Cementitious binder with a binder content of 30% is mixed with the clay slurry, which is poured into the hole to allow curing for 28 days. After the curing stage, the drainage valve is closed to simulate the undrained response of composite ground. Interested readers can find more details in Yi et al. (2016).

2.3. Instrumentation

As shown in Fig. 2, in the middle of the clay layer, a miniature piezometer with a capacity of 100 kPa and an accuracy of 0.1 kPa is installed to provide evidence to terminate the pre-consolidation process. Two miniature earth pressure cells are mounted above the column (with a capacity of 1 MPa and an accuracy of 1 kPa) and the soil (with a capacity of 100 kPa and an accuracy of 0.1 kPa) to record the variations of stress. Similarly, two linear variable displacement transducers (LVDTs) with a capacity of 100 mm and an accuracy of 0.1 mm were attached to two settlement plates for measuring the displacements of column and soil. All readings are recorded by a data acquisition system in every 1 min.

2.4. Experimental program

The model-scale test of composite ground with soil–cement column is conducted in stages. Each load increment is kept at 10.6 kPa for 2 h. There are two termination conditions: (a) the current settlement measurement is more than 5 times the previous measurement, or (b) the present settlement reaches 2 times the previous measurement, but the readings cannot reach the stable condition after 24 h. Upon failure, the previous load increment corresponds to the ultimate bearing capacity of composite ground, q_{cs} . More details about the loading procedures can be found in Yi et al. (2018).

Once the q_{cs} value is measured, the column is excavated to check the failure mode. The extruded column is then cut into two specimens with a length of about 100 mm to conduct unconfined compressive strength (i.e., q_u) tests. The q_u values for T-shaped column are measured as 407 kPa and 477 kPa through the tests on the two specimens, with an average of 442 kPa. Similarly, for conventional column, the strength values are 437 kPa and 409 kPa, with an average of 423 kPa. The q_u values from the four separate specimens are generally consistent, and the slight difference can be induced by the nonuniformity in the column.

2.5. Experimental results

The correlations between stress and settlement measured on the column and the soil for composite ground are plotted in Fig. 3. The curve for untreated ground measured by Yi et al. (2018) is also provided for comparison. It can be seen that when the load increment reaches 116.7 kPa, both the two composite grounds fail, showing a sudden increase of settlement (following a bilinear pattern). At this point, cracks can be observed on the ground surface. Therefore,

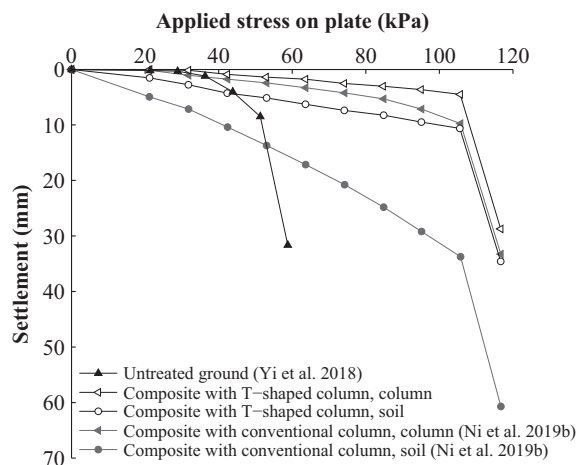


Fig. 3. Comparison of stress-settlement curves for untreated ground, composite ground with conventional column and composite ground with T-shaped column obtained from model-scale laboratory tests.

the load level prior to failure is regarded as the ultimate bearing capacity of $q_{cs} = 105.8$ kPa. One can see that the settlement of column and soil differs heavily. Due to the high stiffness, the settlement of column is less than that of soil. From the nonlinear stress-settlement curve for untreated ground, the bearing capacity is read as 51.4 kPa, but the ground does not fail suddenly. The use of soil-cement column can increase the bearing capacity compared to the untreated ground significantly. It is interesting that the two composite grounds fail at the same load level, suggesting that the failure mode in the two tests is not affected by the implementation of column cap. From previous study, the behaviour of composite ground with conventional column under embankment fill is found to be controlled by column failure (Ni et al., 2019b). With an enlarged column cap, the T-shaped column test shows less

degree of differential settlement between column and soil compared to the conventional column test.

Fig. 4 shows the relationship between stress and time. It should be noted that the column and soil stresses are directly measured through earth pressure cells, based on which the stress on plate can be back-calculated with the mathematical correlation using the area replacement ratio at the column head. One can see that the calculated plate stress is generally in agreement with the applied load in the two tests. The difference could be induced by the positioning error of earth pressure cells. Upon failure of composite ground, the maximum soil stress reaches about 32 kPa and 44 kPa in the T-shaped column test and the conventional column test, respectively, which is still considerably less than the ultimate bearing capacity of untreated ground of 51.4 kPa, demonstrating that soil failure does not occur in both cases. For conventional column, the highest column stress is measured as slightly over 500 kPa, exceeding the unconfined compressive strength of $q_u = 423$ kPa, in which column failure is evident. For T-shaped column, the maximum stress on the column cap approaches about 210 kPa, which is less than the unconfined compressive strength of $q_u = 442$ kPa. This partially indicates that the column cap does not fail due to its larger cross-section, but the column below the cap fails. It should be emphasized that although the failure mode keeps the same in the two composite ground tests, the column cap has changed the stress distribution between soil and column significantly. When a column cap is introduced, the soil stress is obviously reduced, suggesting that more loads are transferred to the column. Load transfer between soil and column can be seen clearly, since the soil stress reduces during the holding stage of each load increment, and the column stress increases slightly. This is due to the arching effect caused by the differential settlement between soil and column (Horpibulsuk et al., 2012; Yi et al., 2016). A buried structure can have a stiffness that is very different from the value for the surrounding soil. Upon loading, significant differential settlement occurs between the soil prism above the column and the soil prism in a close proximity to the column. Therefore, the mobilized friction between the two soil prisms enables stress redistribution in the soil-column system. A structure with a lower deformation can then attract more loads from the surrounding soil, explaining the phenomena of reduced soil stress and increased column stress. Hence, for a composite ground with conventional column under soft fill, the failure mode is governed by soil failure (Ni et al., 2019b), which could be possibly changed by implementing T-shaped column, leading to more load transfer from the soil to the column (column failure controls).

The variation of differential settlement between soil and column with the applied load is plotted in Fig. 5. For T-shaped column, with the increase of load, the differential settlement increases to the maximum of about 6 mm; whereas the largest differential settlement is measured as approximately 25 mm in the conventional column test.

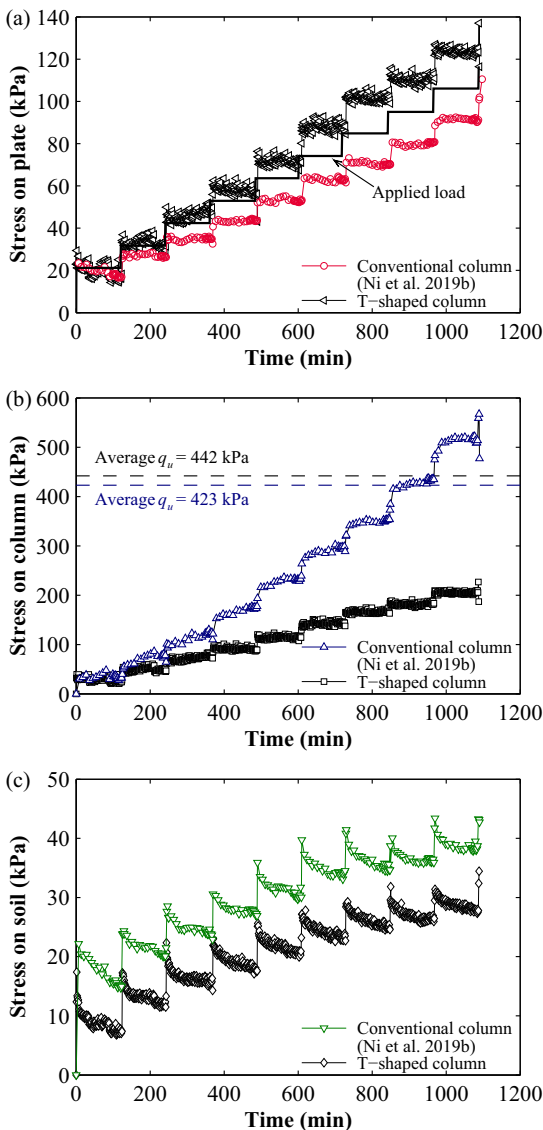


Fig. 4. Time history of measured stresses for composite grounds: (a) on the plate, (b) on the column, and (c) on the soil.

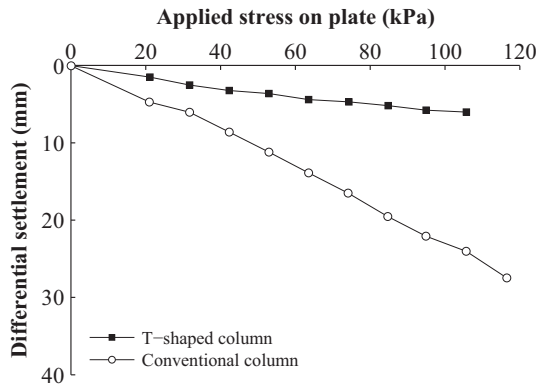


Fig. 5. Measured soil-column differential settlements for composite grounds.

This demonstrates the benefit of using T-shaped column, in which less amount of differential settlement is resulted. The slope of the stress versus differential settlement curve reduces with the increase of the applied load. At a later stage of loading, the displacement compatibility can be reestablished between the soil and the column.

Fig. 6 shows the photo of the failed conventional and T-shaped columns. An inclined shear plane occurs in the conventional column, or in the small-diameter column section of the T-shaped column, which is just blow the column cap. It should be emphasized that some portions are fractured horizontally, which is induced by the manual excavation process rather than the application of loading. The inclined shear plane suggests that column failure occurs during the loading stage. By comparing the measured soil and column stresses in Fig. 4 with their strength values, one can infer that both the soil and the column cap do not fail upon loading. In the T-shaped column test, the sudden failure of composite ground is governed by the failure of column below the cap.

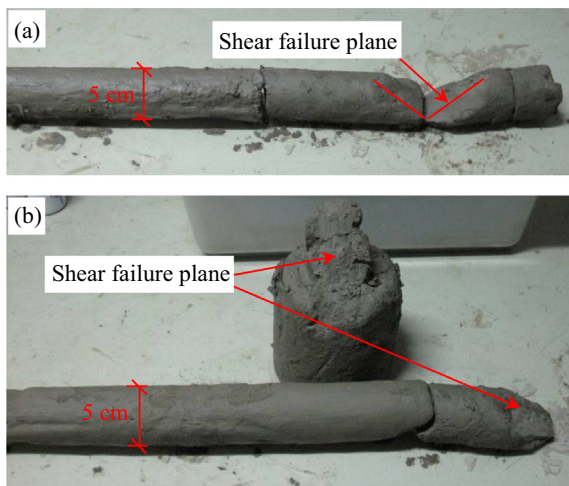


Fig. 6. Photos of excavated columns: (a) failed conventional column (after Ni et al. (2019b)), and (b) failed T-shaped column.

3. Numerical modelling

3.1. Constitutive model

The measured response of composite ground with T-shaped column under embankment fill is employed to calibrate a numerical model. The general-purpose finite element program ABAQUS is used to conduct the analysis. The analysis for conventional column-improved ground is reported in Ni et al. (2019b), and is not repeated herein. Fig. 7a depicts the mesh discretization for the numerical model. Eight-node hexahedral continuum elements are employed to discretize the soil and the T-shaped column. Smooth and rigid boundaries are assigned in the lateral direction, and the bottom of the boundary is fully fixed in all degrees of freedom. The soil-column interface is modelled through a contact approach, which allows sliding with a friction coefficient of 0.2 (Ni et al., 2019b).

The bearing capacity behaviour of composite ground is often simulated under the undrained condition (Abusharar et al., 2009; Voottipruex et al., 2011; Jamsawang et al., 2015; Ni et al., 2019b). The full pre-consolidation is completed in the soft clay layer, such that it can be considered with a short-term friction angle of zero. Researchers found that the use of the standard Mohr-Coulomb model with a cohesion of undrained shear strength is appropriate for clayey soils for short-term analysis (Han et al., 2007; Huang and Han, 2009; Huang et al., 2009; Huang and Han, 2010).

The behaviour of soil-cement column can be considered as undrained, showing a brittle failure once the peak strength is exceeded (Lorenzo and Bergado, 2006; Xiao et al., 2014). The constitutive model for soil-cement column should be able to capture the linear relationship between stress and strain until the peak strength is reached, and the nonlinear strain softening response after the peak (Yapage and Liyanapathirana, 2019). The standard Mohr-Coulomb model has been extensively used to simulate the response of soil-cement column (Han et al., 2007; Huang and Han, 2009; Huang et al., 2009; Huang and Han, 2010), but these studies were mainly focused on the serviceability limit state, rather than the ultimate limit state. Yapage and Liyanapathirana (2019) provided a comprehensive review on the development of constitutive models for cementitious materials with consideration of strain softening. The extended Mohr-Coulomb model is found to be effective to reproduce the behaviour of composite ground with soil-cement column under embankments (Yapage et al., 2014; Yapage et al., 2015), and is easy to be implemented in a numerical model. Hence, the extended Mohr-Coulomb model is adopted in this analysis to simulate the T-shaped soil-cement column.

3.2. Parameters

Results from miniature vane shear tests show the variation of undrained shear strength of soft clay within the

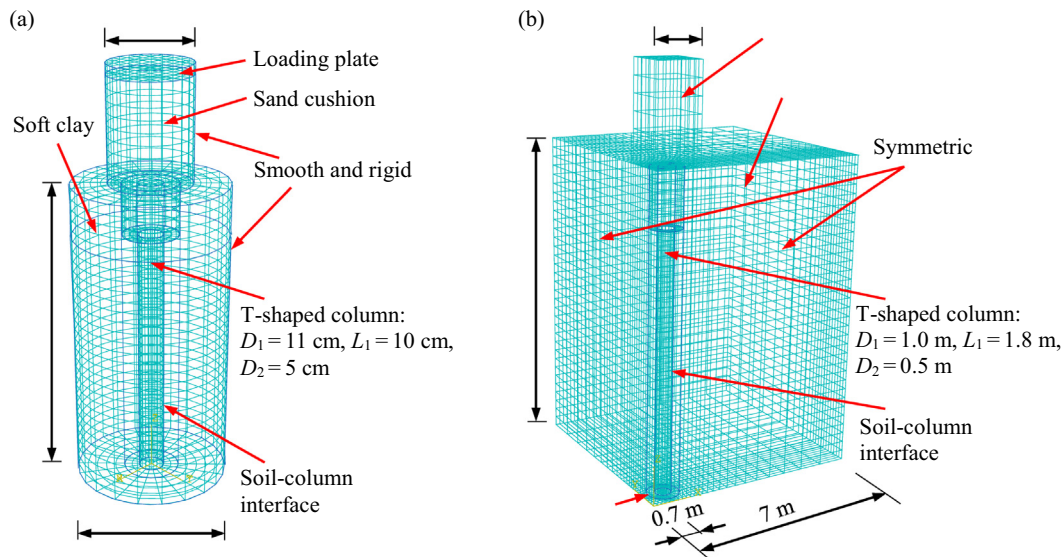


Fig. 7. Finite element discretization of composite ground with T-shaped column: (a) model-scale laboratory test, and (b) parametric analysis.

range of 7–11 kPa. In the numerical analysis, the undrained shear strength of $c_u = 11$ kPa is used to model the undrained behaviour of soft clay, since the upper clay layer influences the bearing capacity of composite ground mostly. Following the work of Ni et al. (2019b), the constrained modulus of clay is taken as 1.5 MPa, and the Poisson’s ratio is assumed as 0.49. The sand, which is completely dry during the test, is characterized under the drained condition, having an elastic modulus of 20 MPa, a friction angle of 35° , and a cohesion of 5 kPa (for convergence consideration) (Ni et al., 2019b).

Previous studies found that the confining pressure does not affect the response of cementitious materials too much, as long as the confining stress is less than the consolidation pressure, at which the shear strength is dominated by cementation bond (Horpibulsuk et al., 2004; Lorenzo and Bergado, 2006; Xiao et al., 2014). Yapage et al. (2015) suggested to model the strain softening behaviour of soil-cement column with a trilinear model, where the peak plastic shear strain, the residual plastic shear strain, and the residual softening index (residual strength over peak strength) fell within the range of 1–4%, 4–15%, and 0.4–0.7, respectively. Based on the studies of Yapage et al. (2015) and Ni et al. (2019b), the peak plastic shear strain of 4%, the residual plastic shear strain of 15%, and the residual softening index of 0.4 are adopted in this study. The elastic modulus (E_{50}) of soil-cement column often ranges from $30 q_u$ to $300 q_u$ (Lorenzo and Bergado, 2006; Abusharar et al., 2009; Voottipruex et al., 2011; Yapage et al., 2014), and $E_{50} = 100 q_u$ is adopted in this analysis. The undrained shear strength of column is derived as $0.5 q_u$ (Yapage et al., 2014; Chai et al., 2015). The Poisson’s ratio of soil-cement column is assumed as 0.49.

3.3. Comparison results

In Fig. 8, the variations of soil and column stresses with settlement obtained from model-scale laboratory test and numerical simulation are compared. The numerical model can generally capture the salient nature of composite ground with T-shaped column under embankment fill. One can see that the soil response is nonlinear in both analyses, whereas the column response follows a bilinear pattern. The bearing capacities for both soil and column are reproduced well, although the settlement from numerical analysis is slightly larger than that obtained from the test. The effectiveness of the numerical model is also demon-

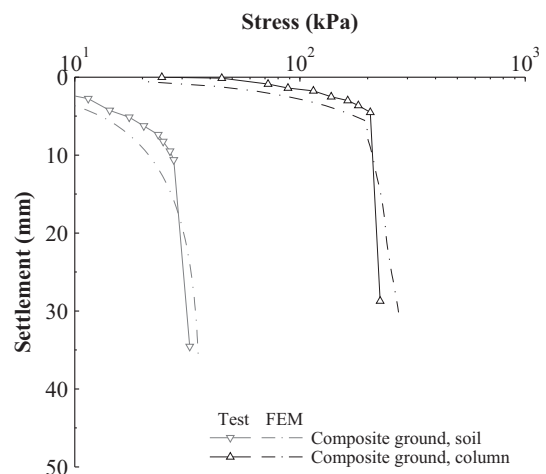


Fig. 8. Comparison of stress-settlement curves for composite ground obtained from model-scale laboratory test and finite element analysis.

strated for conventional column-improved ground previously (Ni et al., 2019b).

4. Parametric analysis

4.1. Analysis scheme

It should be noted that the model-scale laboratory test is conducted on a composite ground with T-shaped column under sand cushion. Compared to the experimental data, the behaviour of composite ground under soft fill can differ significantly, since the failure mode changes from column failure to soil failure (Ni et al., 2019b). Due to the difficulty in simulating the response of composite ground under soft fill, further numerical analyses are carried out. The primary purpose of this study is to optimize the geometry of T-shaped column in composite ground under soft fill for the application of dredging. The influence of geometric and shear strength parameters on the response of T-shaped column-improved ground is evaluated.

A fixed column diameter of $D_2 = 0.5$ m is used, and other parameters vary in the analysis. As tabulated in Table 1, the spacing between columns changes from 1.0 m to 1.4 m, falling within the common range of 1.0–2.2 m (Liu et al., 2012; Ye et al., 2012). These choices of spacing lead to a range of area replacement ratio of $m = 10$ –20%, which is consistent with the suggestion of Yi et al. (2016). The diameter of column cap, D_1 , can vary from the minimum value of D_2 (corresponding to a conventional column with regular cross-section) to the maximum value of S (corresponding to the use of load transfer platform). Therefore, the area replacement area of column cap, m_{cap} , varies from m to 100%. The height of column cap is taken from $L_1 = 0.3$ –2.4 m. If L_1 is too small, punching failure could occur at the column cap; if too large it could result in a significant waste of cementitious materials. In cohesive soils, the unconfined compressive strength of soil–cement column changes from 0.5 MPa to 2.0 MPa (Bruce 2001), such that the current parametric study covers the lower limit. The undrained shear strength of untreated natural soft clay often falls within the range of $c_u = 20$ –30 kPa (Voottipruex et al., 2011; Liu et al., 2012; Chai

et al., 2015). During dredging activities, dredged materials act as fluid with negligible undrained shear strength. In a previous study, an ideal flexible pressure is simulated to characterize the response of dredged slurry (Ni et al., 2019b). In this study, the undrained shear strength of $c_{u,fill} = 1$ kPa is employed to model the behaviour of dredged slurry. Occasionally, clay lump (soft clay) can be excavated during dredging, which needs to be deposited in a dumping site. The clay lump usually has very low undrained shear strength of up to $c_{u,fill} = 10$ kPa (Yan et al., 2013; Ni et al., 2019a). This work adopts a lower limit of $c_{u,fill} = 1$ kPa and an upper limit of $c_{u,fill} = 10$ kPa for comparison.

Square pattern placed T-shaped columns are simulated to establish a one-quarter numerical model as illustrated in Fig. 7b. When the treated soft clay layer is uniform, the bearing capacity of composite ground is not affected by the dimension of the loading plate and the analyzed column number (Ni et al., 2019b). The lateral boundaries near the column are symmetric about the corresponding plane, and the lateral boundaries at the far distance are characterized as smooth and rigid boundaries. The elevation of soft fill is simulated explicitly by the application of gravity with height.

4.2. Failure mode

The stress-settlement curves for two typical cases of composite ground with T-shaped column are plotted in Fig. 9. The difference between the two cases is that the diameter of column cap differs. When the diameter of column cap ($D_1 = 0.7$ m) is close to the column diameter ($D_2 = 0.5$ m), the behaviour of composite ground with T-shaped column is similar to that with conventional column under soft fill, where soil failure controls the mechanism (Ni et al., 2019b). Hence, the stress-settlement curve for column is linear, and the curve for soil shows the high non-linearity. When the D_1 value of 1.2 m approaches the spacing between columns of $S = 1.4$ m, the column cap of T-shaped column has the equivalent function of a load transfer platform (slab). Essentially, the column failure underneath the column cap governs the analysis. One can see the development of differential settlement between soil

Table 1
Summary of parameters in parametric study.

Parameter	Value or range
Column diameter, D_2 (m)	0.5
Spacing between columns, S (m)	1.0, 1.2, and 1.4
Area replacement ratio, m (%)	10, 15, and 20
Diameter of column cap, D_1 (m)	From D_2 to S
Area replacement ratio of column cap, m_{cap} (%)	From m to 100
Height of column cap, L_1 (m)	0.3, 0.6, 1.2, 1.8, and 2.4
Column strength, q_u (MPa)	0.5, 1.0, and 1.5
Undrained shear strength of untreated soil, c_u (kPa)	20 and 30
Undrained shear strength of soft fill, $c_{u,fill}$ (kPa)	1 and 10

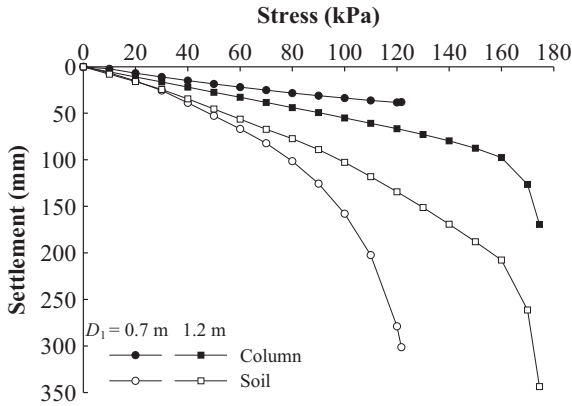


Fig. 9. Stress-settlement curves for composite ground supported by T-shaped column with $L_1 = 0.3$ m, $D_2 = 0.5$ m, a spacing of $S = 1.4$ m, and a strength of $q_u = 1.0$ MPa in soft soils with an undrained shear strength of $c_u = 20$ kPa.

and column, but the stress-settlement curves for both soil and column follow the similar bilinear pattern.

In Fig. 10, contours of zones of shear failure for the two composite grounds with T-shaped column at different spacing are presented to illustrate the failure mode. When D_1 is close to D_2 , there is a continuous plastic zone in the soil (Fig. 10a), while the column is not yield at all (Fig. 10b) in the end of loading stages. This proves that soil failure governs the failure mechanism of composite ground improved by T-shaped column with small column cap under soft fill. It should be emphasized that the current study is conducted for soft clay under the undrained condition. Further study is needed to evaluate the findings for other soils (e.g. stiff soil with a high overconsolidation ratio) or soils under the drained condition. When D_1 is close to S , both soil (Fig. 10c) and column (Fig. 10d) show some plastic zones at an applied stress of 166.5 kPa, none of which becomes continuous (no shear zone yet). With the increase of the applied load (174.5 kPa), obvious shear failure can be seen in the column (Fig. 10f), and a large portion of plastic zones can also be observed in the soil (Fig. 10e). This demonstrates that the failure mechanism of composite ground improved with T-shaped column with large column cap is governed by column failure.

In the case with conventional column, soil failure always governs, and the ultimate bearing capacity is determined when the analysis is terminated (at which continuous failure zone is observed in the soil). In the case with T-shaped column, column failure is the primary mode that controls the behaviour of composite ground, and the stress-settlement curves for both soil and column show nonlinear patterns. Hence, the ultimate bearing capacity of composite ground with T-shaped column can be estimated using the hyperbolic curve tangent modulus method of Li (2008) from the calculated stress-settlement curve.

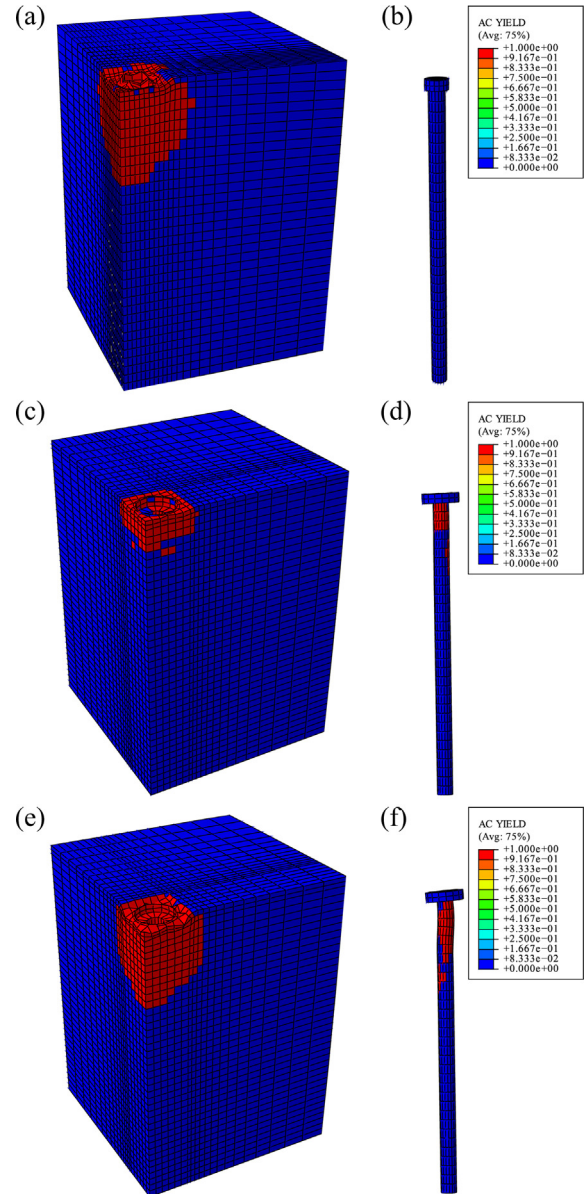


Fig. 10. Contours of zones of shear failure for composite ground with T-shaped column of $L_1 = 0.3$ m, $D_2 = 0.5$ m, $S = 1.4$ m, and $q_u = 1.0$ MPa: (a) yield zones in the soil for the case with a column cap of $D_1 = 0.7$ m at an applied stress of 121.7 kPa, (b) yield zones in the column for the case with a column cap of $D_1 = 0.7$ m at an applied stress of 121.7 kPa, (c) yield zones in the soil for the case with a column cap of $D_1 = 1.2$ m at an applied stress of 166.5 kPa, (d) yield zones in the column for the case with a column cap of $D_1 = 1.2$ m at an applied stress of 166.5 kPa, (e) yield zones in the soil for the case with a column cap of $D_1 = 1.2$ m at an applied stress of 174.5 kPa, (f) yield zones in the column for the case with a column cap of $D_1 = 1.2$ m at an applied stress of 174.5 kPa.

4.3. Optimization

When a composite ground with soil-cement column is designed for use to deposit soft fill (dredged slurry or clay lump), a load transfer platform (slab) is often installed

above the composite ground to enable the mobilization of soil arching (Han and Gabr, 2002; Chai and Pongsivasathit, 2010; Chai and Carter, 2011; Yu et al., 2016). The use of T-shaped column is to replace the conventional approach of load transfer platform (slab). In this way, the mixing work between cementitious material and soft soil does not need to cover the whole region, leading to a considerable cost saving without compromising the bearing capacity.

Ni et al. (2019b) claimed that the ultimate bearing capacity, q_{cs} , calculated for composite ground under either ideal flexible pressure (dredged slurry) or clay lump (soft clay) is very similar. In other words, as long as the undrained shear strength of soft fill, $c_{u,fill}$, is low, the influence of $c_{u,fill}$ is almost negligible. Fig. 11 presents the effect of undrained shear strength of soft fill on the optimization of ultimate bearing capacity of composite ground. It is clear that with the increase of $c_{u,fill}$, the plateau of the q_{cs} versus m_{cap} curve does not shift at all. The difference in $c_{u,fill}$ only results in the change in the slope of the q_{cs} versus m_{cap} curve slightly, before it reaches the plateau. A higher $c_{u,fill}$ is associated with a steeper slope, indicating that the composite ground with T-shaped column under soft clay is easier to enable load transfer from the soil to the column. In other words, the implementation of T-shaped column can fulfill the necessary functional requirement compared to the cast of a load transfer platform easily, when the fill material has a higher strength. With the increase of q_u , the curve moves upwards as expected. It is confirmed that the analyses for dredged slurry and clay lump are equivalent, and the following calculations are conducted on the composite ground with T-shaped column under soft fill with $c_{u,fill} = 10$ kPa.

Fig. 12 illustrates how the variation of height of column cap (L_1) can affect the bearing capacity of composite ground with T-shaped column. When the area replacement ratio of column cap equals to that of column ($m_{cap} = m$), soil failure governs the analysis of composite ground under soft fill, leading to the q_{cs} value of about 100 kPa. The numerically calculated bearing capacity of composite

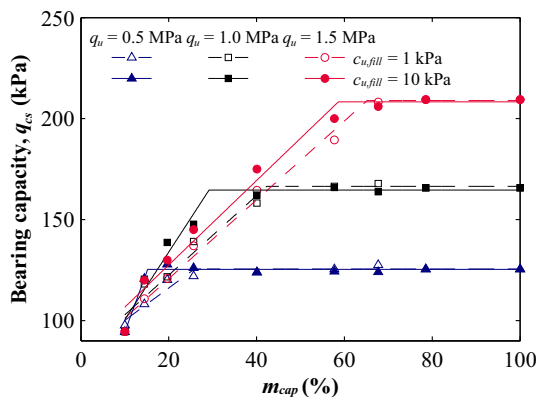


Fig. 11. Influence of undrained shear strength of soft fill, $c_{u,fill}$, on the optimization of ultimate bearing capacity, q_{cs} , of composite ground with T-shaped column.

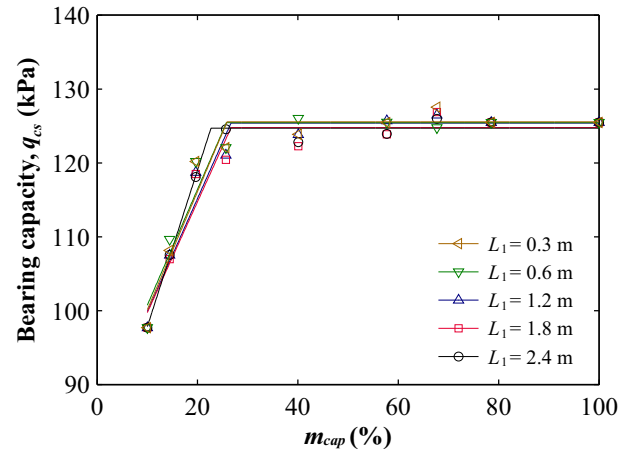


Fig. 12. Influence of height of column cap, L_1 , on the optimization of ultimate bearing capacity, q_{cs} , of composite ground with T-shaped column.

ground with conventional column ($m_{cap} = m$) is close to the theoretical value of untreated ground of $5.14 c_u = 5.14 \times 20 = 102.8$ kPa (Ni et al., 2019b). With the increase of m_{cap} , the calculated q_{cs} increases until it reaches a plateau. In other words, when the m_{cap} value exceeds about 25%, the composite ground with T-shaped column has the equivalent bearing capacity compared to the composite ground with a load transfer platform (slab). It is therefore not necessary to waste a large quantity of cementitious material to form a load transfer platform. When the L_1 value changes from 0.3 m to 2.4 m, the bearing capacity of composite ground does not change. Punching failure could occur in the column cap, if the L_1 value continues to reduce. The minimum height of column height of 0.3 m is suggested for use in practice considering the allowable distance between foldable mixing blades of the construction equipment for T-shaped column.

In Fig. 13, three sets of analyses are conducted, having different area replacement ratio of column, m . One can see that the optimal size of column cap can always be reached for T-shaped column (i.e., there is a plateau in the q_{cs} versus m_{cap} curve), which has the same improvement efficiency compared with the implementation with a load transfer platform (slab). As expected, a higher column strength can result in a higher bearing capacity for composite ground. When the column strength increases, the optimal size of column cap moves to the right, approaching to the use of load transfer platform. This is anticipated, since column failure can hardly occur when the column strength becomes higher. Therefore, a greater zone should be improved to form the column cap to enable load transfer from the soil to the column. It is interesting that the slope of the q_{cs} versus m_{cap} curve does not change much for different q_u values (except for the case of $q_u = 1.5$ MPa). This can provide design implication regarding the optimization of m_{cap} , when a site with different q_u is designed to install T-shaped column under soft fill.

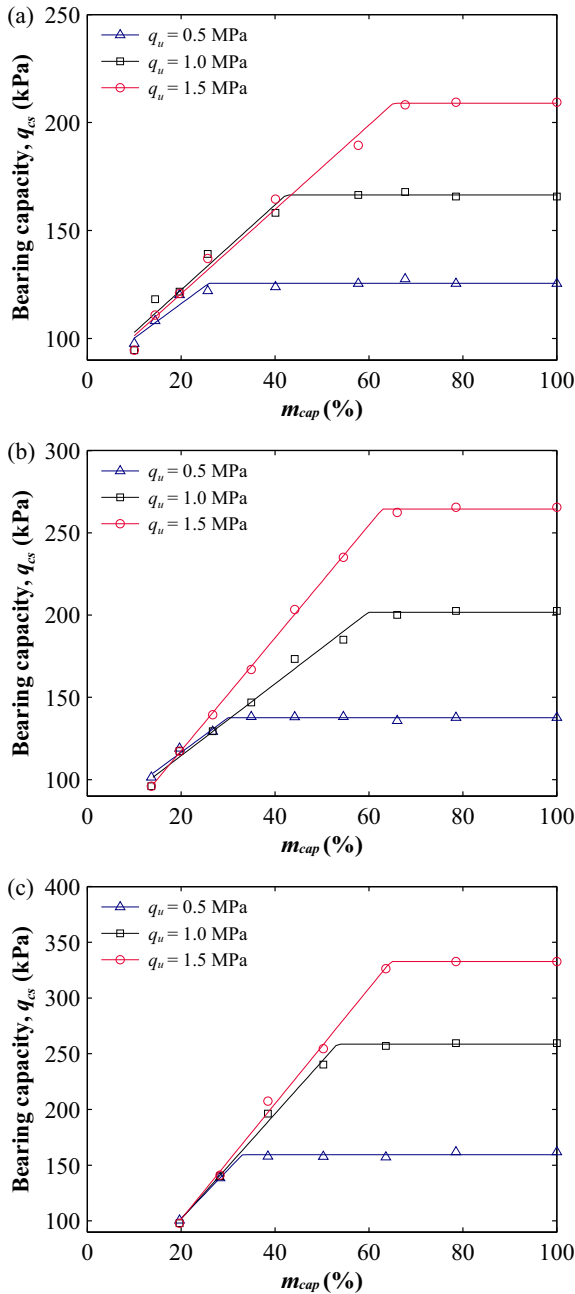


Fig. 13. Optimization of ultimate bearing capacity, q_{cs} , of composite ground with T-shaped column by increasing the area replacement ratio of column cap, m_{cap} : (a) area replacement ratio of $m = 10\%$, (b) area replacement ratio of $m = 15\%$, and (c) area replacement ratio of $m = 20\%$.

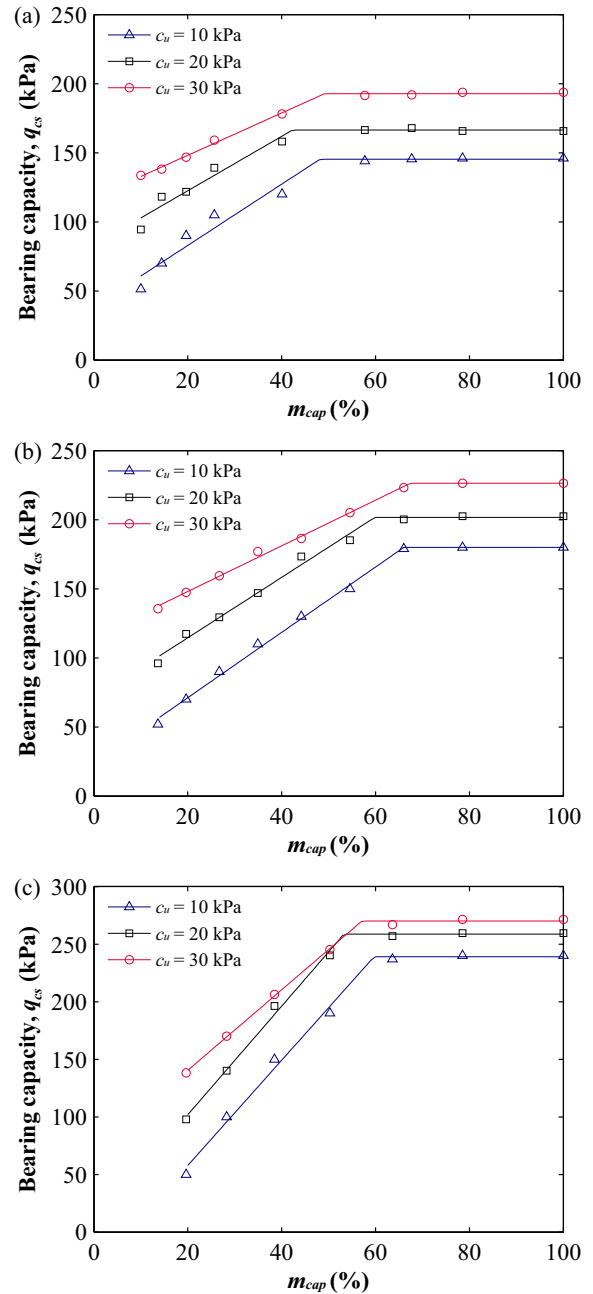


Fig. 14. Influence of undrained shear strength of untreated soil, c_u , on the optimization of ultimate bearing capacity, q_{cs} , of composite ground with T-shaped column: (a) area replacement ratio of $m = 10\%$, (b) area replacement ratio of $m = 15\%$, and (c) area replacement ratio of $m = 20\%$.

Fig. 14 shows the impact of undrained shear strength of untreated soil, c_u , on the optimization of ultimate bearing capacity of composite ground with T-shaped column under soft fill. For a case with a specific m value, the optimal m_{cap} can be calculated, which is found to be nearly independent of c_u . The slope of the q_{cs} versus m_{cap} curve is not very sensitive to the c_u value, but the intercept of each curve (bearing capacity of composite ground with conventional column) differs with c_u . A higher q_{cs} value is obtained when the untreated soil has a larger c_u . Essentially, the difference

in c_u only moves the q_{cs} versus m_{cap} curve in the vertical direction.

5. Conclusions

Since the failure mode of composite ground with conventional soil-cement column under soft fill is usually governed by soil failure, the use of T-shaped column is proposed in this investigation to improve the bearing capacity of composite ground under soft fill, which can

act in a similar manner compared to a load transfer platform. Model-scale laboratory tests are carried out to evaluate the responses of T-shaped column-improved ground, and the experimental data are used to calibrate a numerical model. The numerical model is further employed to optimize the geometry of T-shaped column in composite ground under soft fill. The following conclusions can be drawn:

- (a) For a composite ground with conventional soil-cement column under soft fill, soil failure always governs the design. The use of T-shaped column can change the failure mode of composite ground, where column failure underneath the column cap controls.
- (b) The height of column cap does not influence the bearing capacity of T-shaped column-improved ground under soft fill, and a minimum value of 0.3 m is suggested for use in design to avoid punching failure, considering the size of the construction equipment.
- (c) The diameter of column cap affects the bearing capacity of T-shaped column-improved ground under soft fill significantly. The use of T-shaped column for composite ground under soft fill can provide comparable bearing capacity to the implementation of load transfer platform (slab), as long as the diameter of column cap exceeds a critical value.
- (d) Higher column strength and undrained shear strength of untreated soil can all increase the bearing capacity of T-shaped column-improved ground, but does not affect the optimization of column cap much.

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