Bearing capacity of shallow foundation on column type DMM improved ground

Capacité portante de fondation superficielle sur un sol amélioré avec des colonnes DMM

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ABSTRACT: Bearing capacity of improved ground by column type DMM was investigated by a series of centrifuge model tests and slip circle analyses. The model foundation was subjected to various combinations of vertical and horizontal loads under a 30 *g* acceleration field. It was established a failure envelope in vertical-horizontal load plane. The measured bearing capacity was compared with the calculated by slip circle analyses in order to evaluate the effect of the failure mode of the columns. It was found from the tests that the improved ground possessed a brittle behavior at failure and each DMM columns showed either shear or bending failure mode depending on its location and loading condition. It is pointed out the importance of considering failure mode of the stabilized column for accurate estimation of the bearing capacity of the column type DMM improved ground.

RESUME: La capacité portante de sol amélioré avec collonnes type DMM a été traité par une série de testes centrifuges et par des analyses de surface circulaire. Le model de fondation a été examiné par de différentes variations des charge horizontals et verticals aux conditions d'une accélération de 30 g. On a établi la curve intersèque de rupture dans un plan vertical et horizontal de chargement. La capacité portante mésurée a été comparée avec celle de calculation par l'analyse de surface circulaire pour estimer l'effet de mode de rupture des collonnes. On a trouvé par des testes que le sol amélioré a une conduite fragile lors d'une rupture et chaque collonne DMM montre rupture soit par cisaillement soit par fléchissement en condition de sa position et état de chargement. On a accentué sur l'importance de considérer le mode de rupture d'une collonne stabilisée pour une correcte estimation de la capacité portante de sol amélioré par des collonnes-type DMM.

1 INTRODUCTION

Deep Mixing Method (DMM), a deep in-situ stabilization technique using cement and/or lime as a stabilizing agent, is often applied to improve soft soils. In practice, special equipment, deep mixing machine is used to treat soft soil in-situ, which is basically composed of several mixing blades and stabilizer supplying system. By one operation of the machine, a column of treated soil is manufactured in the ground. In order to manufacture a continuous treated soil mass, these columns are overlapped in a series of operation. According to the scale and importance of the structures, several patterns of improvement are conceived and practiced - e.g. group columns, block, grid and wall type (Terashi & Tanaka 1981).

The group column type improvement has been extensively applied to improve foundation grounds of light-weight structures. Bearing capacity of the group column type improved ground is calculated by a slip circle analysis in Japan, in which a half of unconfined compressive strength is used as a shear strength of the improved column (Kitazume et al. 1996b). Since it is well known that cement treated soil shows relatively small residual strength and is characterized by brittle failure and also the improved ground fails progressively (Terashi & Tanaka 1983), the design method might overestimate the bearing capacity. Tatsuoka and Kobayashi (1983) conducted a series of triaxial compression tests and emphasized that the residual strength should be used instead of the maximum in the slip circle analysis.

The behavior of improved ground has been investigated experimentally by Terashi and Tanaka (1983), Kitazume and Terashi (1991), Kitazume et al.(1996a), etc. It is found that the columns in the group column-type DMM improved ground show various failure modes - shear, bending and tensile failure modes, depending not only on the ground and external load conditions but also on location of each column in the ground. Since the tensile and the bending strengths of the stabilized soil are much smaller than the compressive strength, the column strength used in the analysis should be determined after taking into consideration the failure mode of each column.

The investigation presented in this paper was carried out by centrifuge model tests where a prototype behavior can be simulated in a scaled model by means of the centrifugal acceleration. A series of loading tests was performed on overconsolidated ground improved by the column type DMM to focus upon the effect of the external load condition on the failure mode and the bearing capacity. The measured bearing capacity was compared with the calculated by slip circle analyses in order to show the importance of considering the different failure modes of the columns.

2 MODEL TESTS

The model tests was carried out in the Mark I Geotechnical Centrifuge at Port and Harbour Research Institute (PHRI). The centrifuge had a radius of 3.8 m, the maximum payload of 2.7 tons, the maximum acceleration of 115 *g* and the maximum capacity of 300 *g*-tons. The details of the centrifuge were described by Terashi (1985).

The prototype simulated in this study was a composite breakwater consisting of a concrete caisson and rubble mound which is the most widespread type in Japan. The model tests were defined by the following conditions - the replacement area ratio A_s was high (Table 1); the improved area was symmetrical in regard to the foundation of the breakwater; the DMM columns reached the underlying stiff sand layer. The model setup for the tests is schematically shown in Figure 1.

The soft clay layer was prepared by kaolin clay with following characteristics: liquid limit W_L=59%, plastic limit W_P=16.8%, plasticity index I_P=42.2%, specific gravity of solids G_s=2.692, compression index c_c= 0.49 and coefficient of consolidation c_v=0.2cm^2/min (Kitazume & Terashi 1991). The kaolin clay slurry with a water content of 120% was gradually preconsolidated one-dimensionally under a pressure of 36.7 kPa which was equal to the overburden pressure at the bottom of the soft clay layer in the 30g field. Thus the clay ground had an OCR=1 at its bottom with gradually increasing OCR toward the top. The DMM improved columns were prepared by Kawasaki clay stabilized with 15% (per the dry weight of the soil) ordinary Portland cement. The major index parameters of this clay are: liquid limit W_L=83.4%, plastic limit W_P=38.6%, plasticity index I_P=44.8%, specific gravity of

Table 1. Test conditions and results

Test No	Model ground conditions				Loading condition*	Test Results			
	Number of DMM columns	Unc. compr. strength of columns, q_u kPa	Replacement area ratio, A_s %	Area of columns beneath footing, A cm^2		Vertical load		Horizontal load	
						V kN	$V/(q_u.A)$	V kN	$V/(q_u.A)$
DMMT1	28 [7 x 4]	520	56	50.3	H, V	0.26	0.48	0.151	0.058
DMMT2	40 [8 x 5]	758	79	71.1	H, V	2.85	0.53	-	-
DMMT3	40 [8 x 5]	573	79	71.1	H, V	1.22	0.30	0.251	0.062
DMMT4	40 [8 x 5]	213	79	71.1	H, V	0.61	0.40	0.143	0.095

* ←—— - constant load

←– – – - constant rate of displacement

solids G_s=2.688 and particle size distribution - 2.7% sand, 44.8% silt and 52.2% clay content (Kitazume et al. 1988). The initial water content of the remolded Kawasaki clay was 160% and the curing time of the DMM columns was 15 days. A detail description of model preparation was made by Kitazume et al. (1996a).

The model ground was brought up to a 30 *g* acceleration field, which corresponded to a 6 m soft clay layer improved by the DMM columns of 60 cm diameter in a prototype scale.

Four model tests were performed under various combinations of vertical V and horizontal H load components as shown in Table 1. In the case of DMMT2 only vertical load was applied by means of motor jack with a constant displacement speed of 2.32 mm/min. The ultimate vertical bearing capacity was determined in this test. In the other tests the vertical load was applied by the self weight of the caisson and was kept constant during the horizontal loading. Immediately after reaching the 30 g acceleration, horizontal load component was applied by the motor jack with

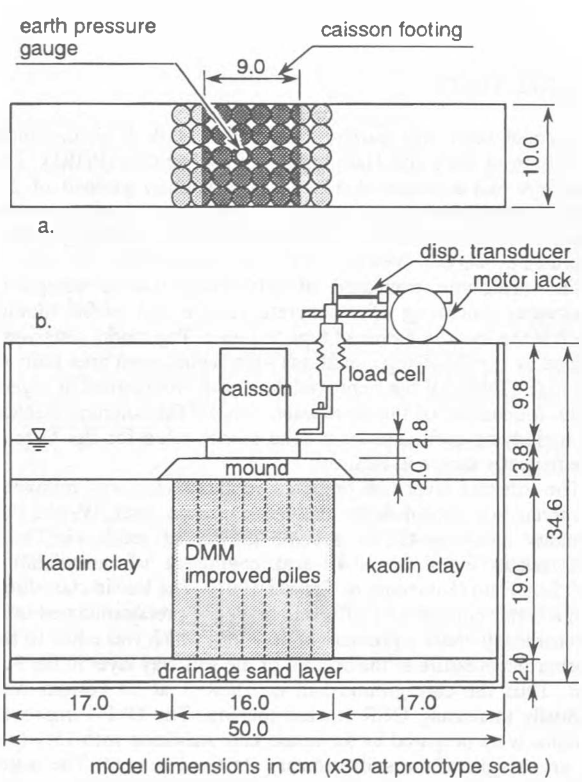

Figure 1. Model setup: a. horizontal cross-section
b. vertical cross-section

a constant loading speed of 6.31 mm/min. Therefore DMMT1,DMMT3, and DMMT4 were bearing capacity tests with inclined load.

All the model tests were carried out in an undrained and plain strain condition. The increments of the horizontal load, displacement of the caisson and earth pressure variation were measured. After the completion of the centrifuge test the strong box was disassembled, and the deformation of the model ground and the failure pattern of the DMM columns were directly observed.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Load - displacement relations*

Load - settlement curve for vertical loading test and load - displacement curves for inclined loading tests are shown in Figure 2 and Figure 3 respectively. In all tests the magnitude of the load increases rapidly with the increase of displacement (or settlement) and clear peak of the load can be distinguished. The load - displacement curves are characterized by a brittle behavior of the improved ground.

Vertical and horizontal components of the bearing capacity are summarized in Table 1. Since q_u of the columns was slightly different in each test and also the replacement area ratio A_s for DMMT1 was smaller than the others, the peak loads are normalized with respect to the product of the q_u and the cross sectional area of the columns beneath the caisson, A.

3.2 *Failure pattern of DMM columns*

Typical examples of failure pattern of DMM columns are shown in Figures 4 and 5 for vertical and inclined loading tests, respectively. In the vertical bearing capacity test (DMMT2), some shear failures can be observed in the columns just beneath the caisson. In this case, a sort of wedge, symmetrical to the center of the foundation, is formed and penetrated into the ground. The columns on both sides of the wedge, on the other hand, show a brittle bending without any shearing (Figure 4). However, the direct observation of the column failure in DMMT4 shows a plain rupture breaking with linear character (Figure 5) in which the segments of the failed column remain straight. In this case, no clear shear failure mode can be found in the column deformation. These observations indicate that the DMM columns failed by different failure modes depending not only on the external load condition but also on location of each column.

Figures 4 and 5 were taken after the loading tests. As mentioned by Terashi and Tanaka (1983), it can be estimated that columns did not fail at the same time but failed one by one during the loading and the improved ground showed progressive failure. Therefore it can be emphasized that the effects of difference in

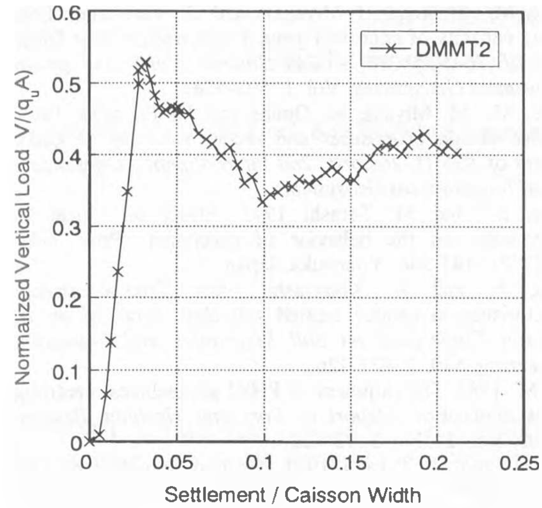

Figure 2. Load - settlement curve for vertical loading test

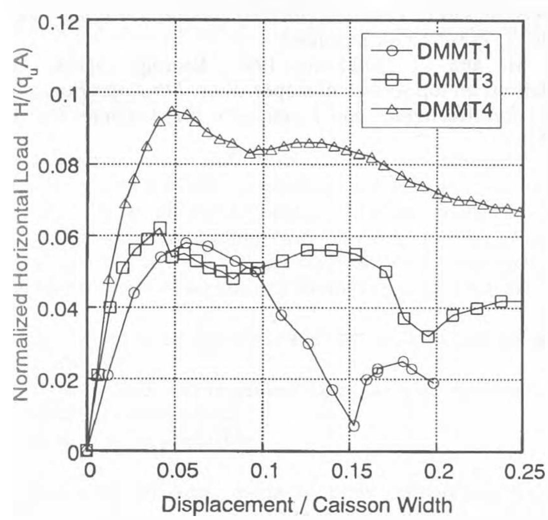

Figure 3. Load - displacement curves for inclined loading tests

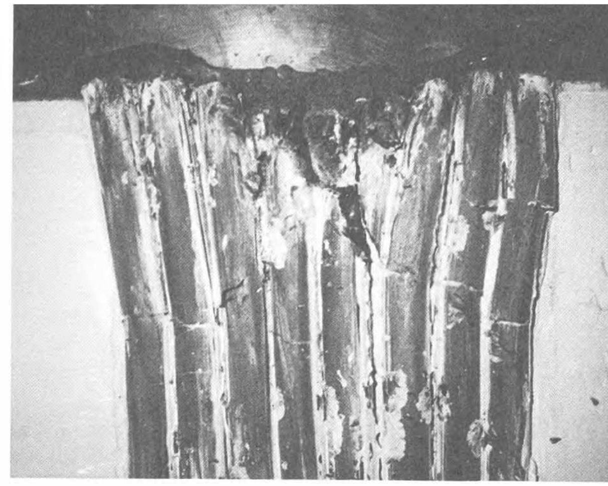

Figure 4. Failure pattern of DMM columns under vertical loading (DMMT2)

Figure 5. Failure pattern of DMM columns under inclined loading (DMMT4)

failure mode and the progressive failure should be taken into account in the analysis in order to evaluate the bearing capacity accurately.

3.3 *Failure envelope*

In order to ascertain the reliability and validity of the above findings, the vertical and horizontal failure loads are plotted in Figure 6. All the data are normalized with respect to the product of q_u*A. The test results show that the horizontal load increases with the increase of vertical load to the maximum at V of about 50 - 75% of the ultimate vertical bearing capacity. After that, the horizontal load decreases rapidly with further increasing of V level. These data form a sort of failure envelope with spindle shape. Similar failure envelope has been found for various types of ground by Terashi and Kitazume (1987) and Gottardi and Butterfield (1993).

3.4 *Slip circle analysis*

In the Japanese current design procedures, the bearing capacity of the group column type improved ground is carried out by a slip circle analysis in which a half of unconfined compressive strength is used as a shear strength of the improved column. Because clay slurry was filled in-between the DMM columns in the model preparation, the strength of the clay was assumed to be zero in the analyses. The calculated failure envelops by the design procedure is plotted by (a-1) in Figure 6. The calculation shows very large failure loads and can not succeed to estimate the test results.

An analysis using a half of the residual strength as a shear strength of the column was also conducted and plotted by (a-2) in the figure. The residual strength of the column was assumed 80% of q_u (Tatsuoka & Kobayashi 1983). It is found in the figure that this analysis also overestimates the test results. In order to coincide with the vertical component of the measured failure load, slip circle analysis with a half of 35% of q_u was also carried out and plotted by (a-3). This analysis still overestimates the horizontal component of the failure load. The performed analyses indicate that the slip circle analysis with consideration of only shear failure mode can not succeed to estimate whole failure envelope reasonably.

Some analyses were next conducted in which the failure modes of each column are taken consideration. Base on the ground deformation shown in Figures 4 and 5, failure patterns of each column in each test are roughly divided into shear or bending failure mode. In the analysis, the shear strengths of the columns divided into 'shear failure' is assumed a half of q_u. The shear strength of 'bending failure' columns is estimated less than the bending strength of the column $_b$ and $_b$ was assumed 10% of q_u (Terashi & Tanaka 1981). The analysis was carried out using above two strengths, and the results is shown by (b-1). It can be

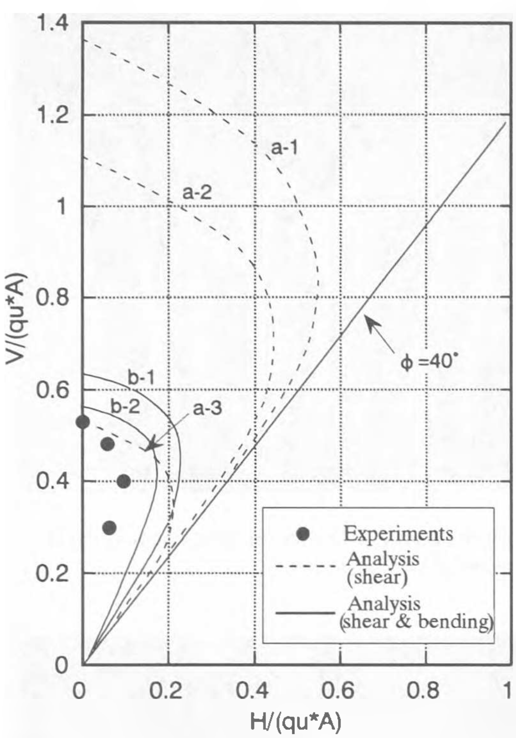

Figure 6. Failure envelope and slip circle analysis

seen that the analysis (b-1) shows relatively well coincidence with the measured value along wide range of V levels. In order to investigate influence of $_b$, the calculation using 10% of $_b$ as a shear strength of the 'bending failure' column is also plotted by (b-2). It is found that the analysis (b-2) shows smaller failure envelope than analysis (b-1) but the difference is not so large.

Although the analyses are based on the simple and rough estimation in failure mode and strength of each DMM column, they indicate the importance of taking account of failure mode to estimate the bearing capacity of the improved ground.

4 CONCLUSIONS

Bearing capacity of the column type DMM improved ground under various loading conditions was investigated by the centrifuge model tests and the slip circle analyses. The major conclusions in this study are as follows:

1) The failure envelope with a spindle shape can be formed in the vertical - horizontal load plane, which is similar to those for various types of ground;

2) The improved ground shows brittle behavior at failure and each column shows either shear or bending failure mode depending on the load condition and its location in the ground;

3) The Fellenius method with only shear failure mode can estimate vertical bearing capacity if suitable mobilization of shear strength can be assumed, but it can not succeed to estimate whole failure envelope. The method with consideration of failure mode of each column can estimate reasonably the bearing capacity envelope. This emphasizes the importance of consideration failure mode to estimate the bearing capacity of the DMM improved ground accurately.

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