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Development and practice of composite DMM column in China

Mise au point et utilisation courante des colonnes DMM composites en Chine

G. Zheng & X.L. Gu
Department of Civil Engineering, Tianjin University, China
G.R. Ling
Institute of Architecture and Construction Design, Tianjin University, China

ABSTRACT
Experimental research and numerical analysis show that the ultimate bearing capacity of DMM (Deep Mixing Method) column is mainly determined by the column strength. Based on that, a new type of composite DMM column is developed by driving a mini reinforced concrete pile into a common DMM column right after its installation to enhance its bearing capacity. This paper reviews a series of experimental research and engineering practice of this new composite column in recent years in China.

RÉSUMÉ
La recherche expérimentale et l'analyse numérique montrent que la force portante limite des colonnes DMM est essentiellement déterminée par la résistance de la colonne. En se basant sur ce résultat, un nouveau type de colonne DMM composite a été mis au point en battant un mini-pieu en béton armé dans une colonne DMM habituelle, immédiatement après son installation, dans le but d'augmenter sa force portante. Cette communication passe en revue une série de résultats expérimentaux et de chantiers où ces nouvelles colonnes ont été utilisées ces dernières années en Chine.

1 INTRODUCTION

In China, where cement treated columns are widely used, DMM columns are often used to support multi-story buildings and even high-rise buildings. The DMM columns, together with the surrounding soil, which are known as composite foundation, are mainly expected to carry vertical load. In practice, traditional DMM columns are usually regarded as piles at certain spacing when designed. Yet, due to the quite limited bearing capacity of each single column, DMM column in composite ground is often installed at a very small spacing in a group or a network. This leads to a comparatively high cost, which sometimes makes it not applicable compared to some other ground improvement methods and even pile foundation. Moreover, in soft ground, DMM column composite foundation sometimes exhibit large settlement and differential settlement due to the low stiffness of cemented soil column, many cases about cracking in super-structure (especially brick structure and brick and concrete mixed structure) have been reported.

2 THE FAILURE MODE AND BEARING CAPACITY OF TRADITIONAL DMM COLUMN

2.1 *The load transfer of axially loaded DMM column*

As that of common rigid piles such as concrete pile, reinforced concrete pile and steel-pipe pile, the bearing capacity of DMM column is composed of shaft resistance and tip resistance. For a long DMM column, research has shown that due to the limited strength and low stiffness, the failure of column usually occurs before its shaft resistance and tip resistance are fully mobilized.

The load transfer mechanism of DMM column was studied by conducting pull-out tests (G. Zheng,1999), the shear stresses mobilized at soft soil-cement treated soil interface and soft soil-concrete interface were measured and compared. The test results showed that there was little difference between the load transfer behaviour at the two interfaces, which indicated that the interface between the DMM column and the surrounding soil had almost the same or even higher shear strength than that of concrete-soil interface. Therefore, a DMM column can achieve the same total shaft resistance as that of a concrete pile of the same perimeter and length. For a long floating DMM column, it may have the same bearing capacity as that of a concrete pile when the tip resistance is too small to be considered compared to the skin resistance. But due to the low stiffness of DMM column, a concept of effective length of single DMM column has been introduced. No further load can be transmitted beyond the depth of the effective length because it has all been shed through shaft friction.

2.2 *The failure mode of axially loaded DMM column*

Loading tests on DMM columns of 10 m long in Zhejiang (J.W. Duan et al.,1994) showed that the failure was caused by the crush of column body approximate 2*D* (*D* is the column diameter) below the column head. The failure patterns of single DMM column of 18 m long and 0.5 m in diameter in soft clay were studied by conducting field loading tests (G. Zheng et al., 2002). The properties of the soft clay are shown in table 1.The thickness (*h*) of different soil stratum is also given in Table 1.

The load *Q* versus settlement *s* curves are shown in Fig.1. The exhumation of columns after loading tests showed that the failure of DMM columns were also caused by the crush of column body near the column head. When unloaded, there was hardly any rebound of loading plate.

Table1 : Soil Physical and Mechanical Properties

h (m)	w (%)	e	I_L	c (kPa)	φ (^{o})	E_{s1-2} (MPa)
1.40	38.2	1.50	0.64	20.4	12.4	3.15
4.60	70.7	1.98	2.07	13.1	7.2	1.07
6.80	70.2	1.97	2.24	13.5	7.7	1.10
>6	52.2	1.49	1.49	14.4	8.6	1.59

According to Fig.1, the average ultimate bearing capacity of the columns is only 140 kN which is much less than the total of the shaft resistance and tip resistance of the column, i.e. the shaft resistance and tip resistance of the column are far from being fully mobilized due to the early failure of column body.

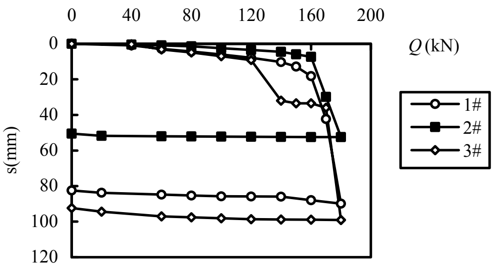

Figure 1. *p-s* curves of single DMM column

In order to further investigate the effect of column strength and stiffness on the bearing capacity of DMM column, two steel pipes of 50 mm in outside diameter and 11 m long were driven into each of the other three DMM columns after the installation of DMM columns. Then composite foundation loading tests, i.e. loading test on the single reinforced DMM column(R1~R3) and surrounding soil are carried, the load *p* versus settlement *s* curves are obtained(Fig.2).The loading plate is 1×1m.

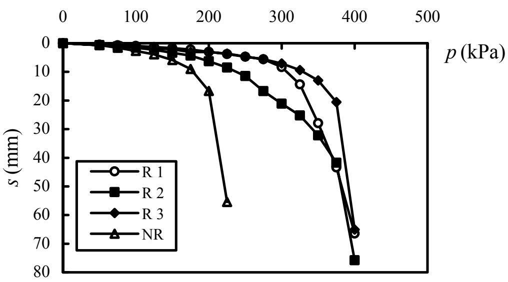

Figure 2. *p-s* curves of DMM composite foundation

The *p~s* curve of a composite foundation loading test on DMM column(NR) without steel pipe in the column is also given in Fig.2. It can be seen from Fig.2 that the bearing capacity of DMM column composite foundation was increased by 78% on average (G. Zheng et al., 2002). It can be concluded that much more shaft resistance and maybe some more tip resistance are mobilized due to the steel-pipe in the columns.

X.J. Li (2004) conducted field loading tests on DMM columns of 7 m long and 0.5 m in diameter in silty clay in Hebei Province. Three loading tests were carried out on composite foundation and other three on single DMM column. The total load *Q* versus settlement *s* curves are shown in Fig.3 and Fig.4 respectively.

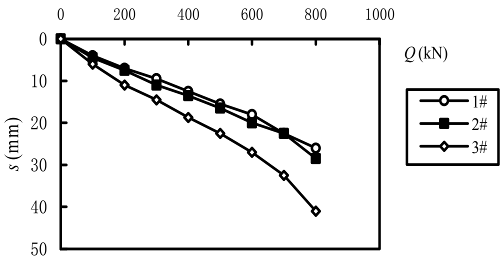

Figure 3. *Q-s* curves of DMM composite foundation

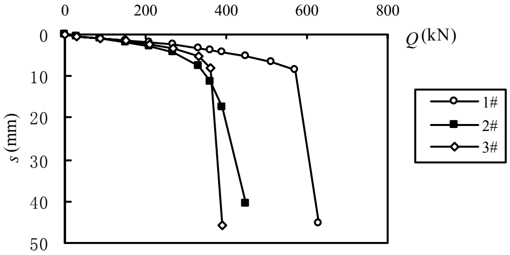

Figure 4. *Q-s* curves of DMM column

In the DMM composite foundation loading test, a layer of sand cushion was placed beneath the loading plate. Due to the sand cushion, the stress concentration on column head was significantly reduced. It seemed from Fig.3 that there was no failure happened even after the total load reached 800 kN and the settlement exceeded 20~30 mm. Yet, as showed in Fig.5, the column head actually cracked under the load (the soil around the column head was excavated and column head was exhumed after loading tests). For single DMM column, it can easily be seen from Fig.4 that all three columns failed just as the column in Fig.5. The picture of DMM column head before the loading test was showed in Fig.6.

Figure 5. DMM column head after single DMM column loading test

Figure 6. DMM column head before loading test

The experimental study above showed that the failure of long single DMM column was mainly caused by the crush or crack of column body owing to its low strength, and all failures happened at a very small settlement. Thus the potential shaft resistance along with the tip resistance of DMM column was not fully mobilized due to the early failure of column head.

3 FIELD EXPERIMENTAL RESEARCH OF COMPOSITE DMM COLUMN

As mentioned above, due to the comparatively much lower stiffness and column strength (unconfined compressive strength of treated soil in soft clay is normally less than 1.5MPa), the bearing capacity of a single column is rather low. Thus a large number of DMM columns at very small spacing are needed to obtain a comparatively higher composite foundation bearing capacity. In addition, as indicated above, the skin resistance and tip resistance of a long DMM column usually can not be fully mobilized before the failure of column (J.W. Duan et al.,1994; G. Zheng et al, 1999). If the bearing capacity and the stiffness of single column can be improved, much less columns would be needed and much higher composite foundation bearing capacity can be obtained.

Fortunately, a so called composite DMM column in China has been developed by driving a mini reinforced concrete pile with diameter of 150-350 mm into the body of the column right after the column being installed, as shown in Fig.7. This is expected

Figure 7. Mini pile driving after DMM column installation

to solve the insufficiency of strength and stiffness of common DMM column so a much greater bearing capacity can be be obtained.

3.1 *The bearing capacity of composite DMM column*

A series of field tests were performed to investigate the failure pattern, bearing capacity and design method of composite DMM column in China (G. R. Ling et al.,2001, P. Dong et al., 2002) in recent years.

Totally 24 field loading tests were carried (G. R. Ling et al., 2001) to investigate the difference in bearing capacity and failure pattern among composite DMM column, traditional DMM column and reinforced concrete bored pile. 7 common DMM columns, 5 reinforced concrete bored piles and 12 composite DMM columns were constructed on the same ground. The length *L*, diameter *D* and ultimate bearing capacity R_u of composite DMM column (CDMM), DMM column and bored pile (BP) are listed in Table 2. The shape of mini concrete pile is like a cone with bigger diameter D_{top} at its top and smaller diameter D_{tip} at its tip. The loading test results of composite DMM column and bored pile of 10.0 m long and of 8.5 m long are shown in Fig.8 and Fig.9 respectively.

Table 2: List of Composite DMM, DMM and Bored Pile

No	Pile type	*L* (m)	*D* (m)	Mini core pile *L* (m)	Mini core pile D_{top}/D_{tip}	R_u (kN)
1	CDMM	8.5	0.5	3.5	200/100	300
2	CDMM	8.5	0.5	5.0	180/180	400
3	CDMM	8.5	0.5	5.0	180/180	500
4	CDMM	8.5	0.5	5.0	250/100	700
5	CDMM	8.5	0.5	5.0	300/100	700
6	CDMM	8.5	0.5	5.0	300/100	600
7	CDMM	10.0	0.5	5.0	300/100	700
8	CDMM	10.0	0.5	5.0	400/100	700
9	CDMM	10.0	0.5	6.0	400/100	800
10	CDMM	10.0	0.5	6.0	400/100	900
11	CDMM	10.0	0.5	7.0	450/100	900
12	CDMM	11.5	0.5	10.0	300/100	1000
13	BP	8.5	0.5			500
14	BP	8.5	0.5			480
15	BP	10.0	0.5			600
16	BP	10.0	0.5			550
17	BP	11.5	0.5			650
18	DMM	6.5	0.5			150
19	DMM	6.5	0.5			180
20	DMM	8.5	0.5			150
21	DMM	10.0	0.5			150
22	DMM	10.0	0.5			150
23	DMM	11.5	0.7			540
24	DMM	11.5	0.7			480

The test results showed that the bearing capacity of composite DMM column was greatly increased compared to traditional DMM column of the same cross section area and length. It even exceeded that of bored pile by 30% on the average. All the results implied that the skin resistance and tip resistance of the composite DMM column had been fully mobilized as long as the mini pile is long enough and its cross section area is big enough. Moreover, calculation based on current code proved that nearly the same capacity as that of precast concrete pile can be obtained with comparatively much lower cost.

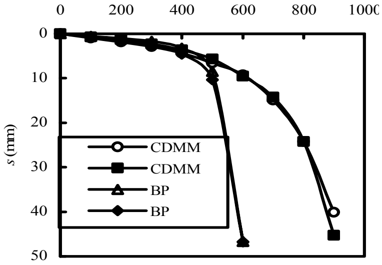

Figure 8. *Q*~*s* curve (*L*=10.0m)

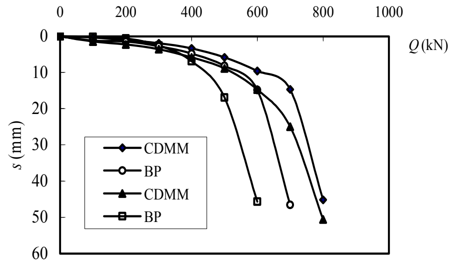

Figure 9. *Q*~*s* curve (*L*=8.5m)

3.2 *The failure mode of composite DMM column*

Based on the load transfer mechanism of composite DMM column, the possible failure patterns may be classified into three as following:

(a) Crush or crack of mini pile (Fig.10). This may occur at certain depth usually when the length of mini pile is big enough but cross section dimension is comparatively small;

(b) Crush or crack of DMM column body near the tip of mini pile. This is usually due to that mini pile is not long enough to make the first and the third failure pattern possible.

(c) The downward penetration of whole composite DMM column. The soil below the column tip yields and slip happens at the interface between column periphery and the surrounding soil. The strength of the composite column reinforced by mini pile must be large enough to make the failure pattern possible.

Figure 10. Crush of mini pile exhumed after loading test

It can be seen from Table 2 that for the composite DMM column, the bearing capacity increased with increased mini pile length until a critical length was reached, i.e. the length of mini pile must be big enough for the shaft resistance and tip resistance of DMM column to be fully mobilized.

Field tests (P. Dong et al., 2002) also showed that the failure of composite DMM column could be due to the crush of mini pile or the penetration of whole column.

Yet, the failure mechanism of composite DMM column is very complicated and needs to be further investigated.

4 PRACTICE OF COMPOSITE DMM COLUMN

In recent years, a lot of buildings supported by composite DMM columns have been constructed in Tianjin, Henan, Shanghai et al. The composite DMM column can be regarded as pile rather than a type of ground treatment and follows the code of pile foundation JGJ94-94.

There are several construction methods in practice. The mini reinforced concrete pile can be driven into DMM column by using static pile press-extract machine, or by vibro-pile driver. In 2004 (G. Zheng), a new type of composite cemented soil, named as Composite Rammed Cemented Soil Column (CRCSC) has been developed and an national inventive patent application has been submitted.

In June 2004, 183 multi-storey building were constructed in Dongli Lake, a famous beauty spot in the east suburb of Tianjin. Due to the soft ground, pile foundation or ground treatment was need. The soil properties are shown in Table 3.

The bearing capacity of 6 prestressed-concrete tubular piles (PTP in Table 4), 6 precast reinforced concrete piles (PCP in Table 4) and 3 composite DMM columns were compared by conducting full-scale loading tests. The parameters of CDMM, PTP and PCP, and their ultimate bearing capacity are shown in Table 4. The load Q versus settlement s curves of loading tests on them are given in Fig.11.

Table 3: Soil Physical and Mechanical Properties

soil	h (m)	w (%)	e	I_L	c (kPa)	φ (^{o})	E_{s1-2} (MPa)
C	3.1	35.8	1.01	0.76	17.9	8.5	3.16
MC	5.3	47.9	1.35	1.15	3.9	5.3	2.47
SC	5.4	24.9	0.69	0.95	20.4	13.3	5.77
silt	1.4	22.4	0.64	0.59	16.6	21.1	7.80
SC	4.9	24.5	0.69	0.59	16.8	10.2	4.89
silt	6.5	23.3	0.64	0.78	18.9	19.4	10.0

Note: C-clay, MC-mucky clay, SC-silty clay

Table 4: Pile Parameters and Ultimate Bearing Capacity

Type	n	L(m)	Cross section(mm)	$\overline{R}_{\mathrm{u}}$ (kN)
CDMM	3	12	D=600	793
PCP	3	12	350×350	660
PCP	3	17	350×350	800
PTP	3	11	D=400	480
PTP	3	17	D=400	640

Note: n is number of piles; $\overline{R}_{\mathrm{u}}$ is the ultimate bearing capacity.

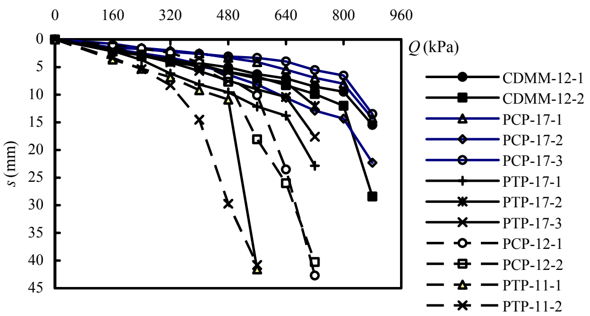

Figure.11 Q~s curves of single pile loading test

Figure.12 Mini reinforced concrete piles used in Dongli Lake

Fig.12 shows the mini precast jointed reinforced concrete pile used in this project. Each of the 2 units of the pile is of 5 m long. The pile is of square cross section of 350×350 mm at the top and 150×150 mm at the tip.

The loading tests were carried by using maintained load test method specified by Building Pile Foundation Test Technique Code JGJ106-2003. Each load increment were held for 2 h except for the final load increment which was held for 1 h to 2.5 h depending on the movement caused by the final load increment. If the total movement of pile head caused by load Q_i exceeded 40 mm, or the increment of movement of pile head caused by load increment ΔQ_i is 5 times bigger than that caused by the load increment ΔQ_{i-1} applied before ΔQ_i, then total load Q_i is the ultimate load and Q_{i-1}, i.e. $Q_i - \Delta Q_i$, is the ultimate capacity R_{u} according to JGJ106-2003.

It can be seen from Table.4 that the bearing capacity of composite DMM column is the highest in the mean with the lowest cost among the three types of piles of nearly the same length. So more than 10000 composite DMM columns of 12 m long, reinforced with mini concrete pile were used in this project.

5 SUMMARY AND CONCLUSIONS

As traditional DMM column composite foundation and other cement treated column are now widely used, the economical consideration has attracted much attention. For a traditional DMM column with low bearing capacity, a column network with small spacing is usually needed to support the super-structure. In addition, a raft foundation is often needed, which will give rise to the high cost. In recent years, rigid pile composite foundation, where the concrete piles with diameter usually less than 500 mm are used as reinforcement, has begun to be popular due to that it can provide much higher capacity than that of a traditional DMM column composite ground.

The composite DMM column can provide as much bearing capacity as a concrete pile does with 30%-50% reduction in the cost, so it has been gradually applied to substitute for common rigid pile in rigid pile composite foundation. Much application has been reported. Yet further research should be carried to investigate the construction quality test such as integrity test, and the behavior of composite DMM column under horizontal load.

REFERENCES

Duan J.W. 1994. Load transfer mechanism of DMM column. *Chinese Journal of Geotechnical Engineering*, July,1994, No 4,1～7.

Dong P. et al. 2002. Use of concrete-cored DCM pile in soft ground. *Chinese Journal of Geotechnical Engineering*, March 2002, No 2, 204-207.

Ling G. R. et al. 2001. Experimental study on concrete core mixing pile. *Journal of Building Structure*, April 2001, No 2, 92-96.

Li X.J. 2004. Theoretical research and practice of DMM composite foundation. Mphil thesis, Tianjin University.
Zheng G. & Jang X.L. 1999. Research on bearing capacity of cement treated column composite foundation. *Rock and Soil Mechanics*, No 4, 46~50.
Zheng G. et al. 2002. Bearing capacity of composite foundation with super long cement treated column in soft soil. *Chinese Journal of Geotechnical Engineering*, December 2002, No 6, 1-5.