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The test and design of multi-direction-jammed piles

Epreuves et études des pieux de compactage en multi-direction

Cai Dezhuang – *Beijing, Institute of Nuclear Engineering, People's Republic of China*
Cai Ming & Zhang Dengxia – *Institute of Mechanics, Academia Senica, People's Republic of China*

ABSTRACT: In this paper, the test and design for a new type of pile, which is named Multi-Direction-Jammed(MDJ) pile, is reported. The MDJ pile is such a filling pile that there is a protrusive disk at its bottom and many tooth blocks which are distributed regularly along its periphery. The holes around the pile's periphery and under end are formed with jamming the soil by using a special equipment, and it is expected to reach the optimum state in Soil Mechanics. In a series of model tests made by the authors, the MDJ pile was compared with conventional piles, the results conclusively showed the bearing capacity of MDJ pile grows by a factor of three even more, the settlement greatly decreases, the concrete consumption saves 70% or more and the cost is obviously conserved as well.

RESUME: Le présent texte expose les épreuves et études des pieux de nouveau type en Multi-Drection-Jammed (MDJ), ces pieux se constituent en beaucoup de blocs en dents et de plateaux coulés Sur place. Les trous des pieux se forment à l'aide de dispositifs spéciaux refoulant le sol, done cela peut faire parvenir les efforts du sol à l'optimum. On constate en évidence, par les essais analogiques sériels de l'auteur, que la charge de pieux MDJ est plus élévee de plus de 3 fois que celle de pieux généraux, en épargnant le béton de plus de 70%, diminuant beaucoup de tassements, abaissant aussi l'ensemble de frais.

1. INTRODUCTION

For the last half century, engineers and technicians have been researching and improving in material, shape and construction technique of piles, and a lot of achievements have been made. For example, the Multi-Under-Reamed(MUR) pile (MOHAN et al. 1969) was developed in India, the Cast-in-Situ Hollow pile (BAKHOLDIN et al.1966) in USSR, the Artificially Reamed pile (Li et al. 1987) in China and the Multi-Explosive Expanded pile et al (Fourth Design Institute 1976). Recently, a machine to form the MDJ pile is developed (Cai 1994),and it is obviously improved in the construction technique. Because the holes to the tooth blocks on the periphery and the protrusive disk at the bottom are formed with the soil being jammed by special equipments, the loading state in the soil is improved, and the capacities of compression and shear resistance are enhanced. Therefore, compared with conventional piles, the bearing capacity of MDJ piles grows by a factor of three even more, the settlement greatly decreases, the concrete consumption saves 70% or more and the cost is obviously conserved as well. If compared with Multi- Under-Reamed (MUR)pile , besides the bearing capacity increases yet and the concrete consumption decreases, the MDJ pile is more convenient than MUR pile in construction.

2. TEST OF PILES

2.1. Purpose of the tests

In order to check the behaviours of MDJ piles and to find the difference between MDJ piles and conventional piles, a series of model tests were conducted, with the soil behaviours, loading and settlement survey being in the same conditions. The samples are classified as two groups, e.g. MDJ piles and conventional piles, and there are five types in total(see Fig. 1).
Fig. 1 a and Fig.1 b are conventional columniform piles. Fig.1 c, Fig.1 d and Fig. 1e are MDJ piles. And the pile in Fig.1e is similar to the MUR piles . There is a great difference that the holes around the protrusive disks and under the tip of piles are formed with the soil being jammed by the special hydraulic equipments, When the pile being practically used in engineering. The protrusive disks of the former two types of MDJ piles are treated as several independent tooth blocks and they are arranged alternately on different planes, so that the sheared periphery surface area is enlarged, and the pressure distribution in the soil is more uniform.

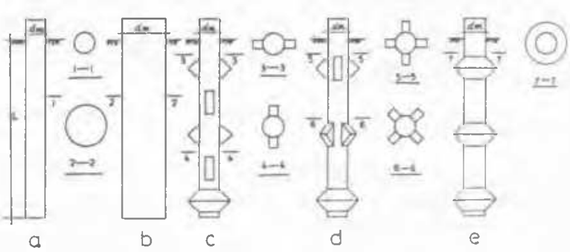

Figure 1. Identification of Tested Piles.

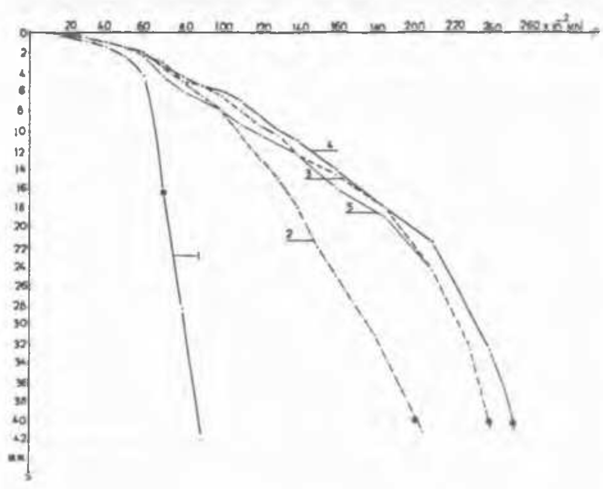

Figure 2. Compression Load-Settlement Curves for Piles No.1, No.2, No.3, No.4 and No.5.

Table I

No.	Type	Effective Length L (cm)	Diameter dm(cm)	Ultimate bearing capacity ($\times 10^{-2}$KN)	Allowable bearing capacity ($\times 10^{-2}$KN)	Concrete Volume
1	Ordinary pile (Column)	20	2.4	70	35	108.6
2	Ordinary pile (Column)	20	5.2	200	100	510
3	MDJ pile (with two tooth blocks on the same plane)	20	2.4	240	120	139.1
4	MDJ pile (with four tooth blocks on the same plane)	20	2.4	260	130	139.1
5	MDJ pile (with a protrusive disk on the same plane)	20	2.4		110	178.8

Notes: 1. The distance between any two layers of tooth blocks along the shaft length of pile No. 3 is as half as that of pile No. 4.
2. No.1,2,3,4 and 5 corespond to Figure1 a,b,c,d and e respectively.

2.2. Result from the tests(see Table I)

The ultimate bearing capacity and allowable bearing capacity listed in Tab. I can be obtained in the following ways.

Curve No. 1 in Fig. 2, which is corresponding to pile No. 1, represents the compression load-settlement curve, e.g. p-s curve. If the load to the second turning- point, from which the curve scrappily goes down, is taken as the ultimate load, e.g. $Pu=70\times10^{-2}$KN, then the axially allowable compression bearing capacity of single pile is $Pa=Pu/2=35\times10^{-2}$KN.

The settlements to each steps of load acting on pile No.2 is stable and the p-s curve goes down slowly. So is the load corresponding to the settlement $\Delta=40$ mm taken as the ultimate load, e.g. $Pu=200\times10^{-2}$KN and the axially allowable compression bearing capacity of single pile is $Pa=100\times10^{-2}$KN.

The p-s curves to piles No.3, No.4 and No. 5 are waved in some local positions, however , according to the changing trend, the p-s curves go down slowly too. Thus for pile No.3, we have $Pu=240\times10^{-2}$KN, $Pa=120\times10^{-2}$KN, and for pile No.4, $Pu=260\times10^{-2}$KN, $Pa=130\times10^{-2}$KN. As to pile No.5, we have $Pa=110\times10^{-2}$KN and at the same time the settlement corresponding to the allowable bearing capacity can not be more than 10mm, e.g. $\Delta\leq10$mm.

2.3. Analyses for p-s curves

There are obvious differences between the p-s curves of MDJ piles and conventional piles. Take the curves for piles No.1 and No.3 as the example.(see Fig.3)

Pile No.1 is a conventional columniform pile, its diameter is dm=2.4 cm. For part OA_1, the relevant load is from 0 to 57×10^{-2} KN the settlement is little, which represents that the acted load keeps less than the side ultimate friction, and the observed top settlement resulted from the elastic compression of the soil and the pile itself . For part A_1B_1, the relevant load is from 57×10^{-2}KN to 70×10^{-2}KN, the curvature of p-s curve is getting smaller and the settlement is larger, which represents that the acted load exceeded the side ultimate friction, because a part of the load is conducted to the soil through the pile's heel and the soil under the pile's tip is locally jammed and these lead to the increment of settlement.

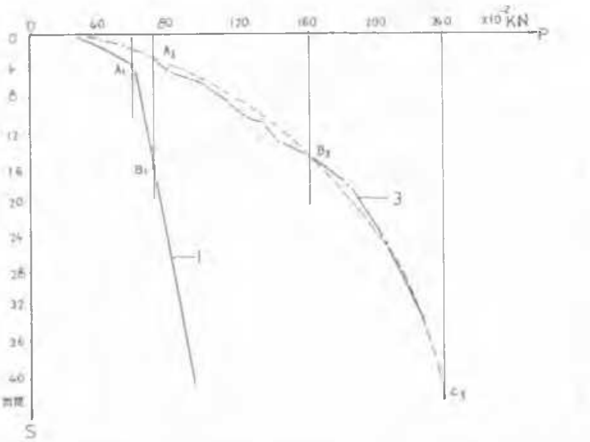

Figure 3. Compression Load-Settlement Curves for Piles No.1 and No.3

After point B_1, the corresponding load is 70×10^{-2}KN, the p-s curve goes down directly, it means that the load exceeded the ultimate friction and the resistance which the soil is jammed out from the pile's tip. They lead to the sharp increment of the settlement of the pile, which reached the ultimate load of the pile, $Pu=70\times10^{-2}$ KN.

Pile No.3 is a new type pile, e.g. MDJ pile, with two tooth blocks on a horizontal plane, and its diameter is dm=2.4 cm.

For part OA_3, the relevant load is from 0 to 70×10^{-2}KN, the settlement is little, and the p-s curve is smooth, which represents that the acted load is supported only by the side ultimate friction, and the observed top settlement resulted from the elastic compression of the soil and the pile itself.

For part A_3B_3, the relevant load is from 70×10^{-2}KN to 160×10^{-2} KN, the p-s curve is waved and not smooth, which represents that the tooth blocks played its roles, the acted load on the pile is supported not only by the friction on the pile and its tooth blocks, and the soil under the tooth blocks, which is jammed further and can support the above load .The tooth blocks are arranged in many layers, the soil under each layer are jammed in different time, so the p-s curve takes the shape of steps. The increment of settlement results not only from the elastic compression of the soil and the pile itself , but also from the jamming of the soil under the tooth blocks.

For part B_3C_3, the relevant load is from 160×10^{-2}KN to 240×10^{-2} KN, the curvature of the p-s curve is getting smaller and the settlement is larger, which represents that the acted load exceeded the side ultimate friction of the pile and the resistance which the soil is jammed out from tooth blocks. because a part of the load is conducted to the soil through the pile's protrusive disk, the soil under the pile's tip is locally jammed and these lead to the increment of settlement.

After point C_3, the corresponding load is 240×10^{-2}KN, the curvature of the p-s curve is getting smaller further ,and the settlement goes down almost directly. It means that the load exceeded the ultimate friction and the resistance which the soil under the tooth blocks and the pile's tip is jammed out . They lead to the sharp increment of the settlement of the pile, the ultimate load of the pile, $Pu=240\times10^{-2}$KN, being reached.

From the above analysis and the comparison between two p-s curves relation to conventional pile and new type pile respectively, it can be seen that the tooth blocks give a obvious affection on the increment of the bearing capacity of piles. When the holes to tooth blocks are formed by a special equipment, the shear and compressive resistance of the jammed soil is increased, which encouraged the increment of the bearing capacity of piles. Therefore, the quality of the construction is the key to the increment of the bearing capacity of this new type pile.

3. ESTIMATE FORMULA OF NEW TYPE PILE

The axially allowable compression bearing capacity of single pile should be determined after the static load tests on site. The number of pile samples under the same conditions should not be less than 1% of total piles, and not be less than two piles. But when designing, before determining the number and the distribution of piles, their bearing capacity must be estimated. In terms of the experience and the results from model tests, the estimate formula for new type piles are suggested as below (see Fig.4).

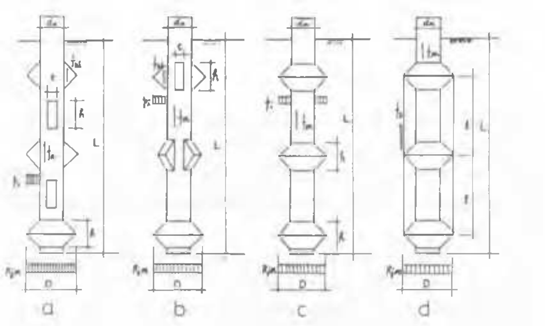

Figure 4. Skeleton Figure of Tested Piles for Calculation.

3.1. The formula for the axially allowable compression bearing capacity of a single pile with tooth blocks (see Fig.4a and Fig.4b):

$$P_a=P_{Rm}+P_{Fm}+P_{Pb}+P_{Fb} \quad (1)$$

where:

$$P_{Rm}=C_1AR_{jm}$$

$$P_{Fm}=[\pi d_m(L-h)-knht]f_m$$

$$P_{pb}=\sum_{i=1}^{k-1} C_2A_{Pb}P_i$$

$$P_{Fb}=\sum_{i=1}^{k-1} C_3A_{sb}f_{bi}$$

Pa = axially allowable compression bearing capacity of a single pile (KN).
P_{Rm}= allowable bearing pressure of the main pile (KN).
P_{Fm}= allowable friction of the main pile (KN).
P_{Fb}= allowable friction of blocks (KN).
P_{Pb}= allowable bearing pressure of blocks (KN).
k = number of the layers of tooth blocks.
n = number of tooth blacks on one layer.
A_{Pb} = horizontal projection area of tooth blocks (m^2).
A_{Sb} = surface area of the two sides of a tooth block (m^2).
C_1,C_2 and C_3 are jamming factors of soil, obtained from the test on site, in general, $C_1=C_2=C_3=1-1.5$.
h, t, dm, L, see Figure 4.

3.2. The formula for the axially allowable compression bearing capacity of a single pile with protrusive disks (see Fig.4c and Fig.4d):

$$P_a=P_{Rm}+P_{Fm}+P_{Pb} \quad (2)$$

Equation (2) is available for Fig. 4c.

Where:

$$P_{Rm}=C_1AR_{jm}$$

$$P_{Fm}=\pi d_m(L-kh)f_m$$

$$P_{Fb}=\sum_{i=1}^{k-1} C_2\pi/4(D^2-d_m^2)P_i$$

$$P_a=P_{Rm}+P_{Fs}+P_{Fm} \quad (3)$$

Equation(3) is available for Fig. 4d.

Where:

$P_{Rm}=A\ R_{jm}$
$P_{Fs}=(k-l)l\pi D\ fs$
$P_{Fm}=\pi d_m[L-(k-1)l]f_m$

f_{bi}=allowable friction of the blocks (KPa).
fs= allowable friction of the pile and soil combination against the soil, determined by tests on site. In general, fs=(1-1.5)fm.
fm = allowable friction of the soil on pile's periphery, when there are different soil layers, fm = the weighted average of all soil layers(KPa).
Pi = allowable bearing capacity of the soil under the tooth blocks(KPa)
C_1 and C_2= jamming factors of soil, obtained from the tests on site, in general, $C_1=C_2=1-1.3$. When the soil is repeatedly and compressionally stressed, $C_1=C_2=1$.
A= horizontal projection area of bottom of the pile (m^2)
Rjm= allowable end bearing pressure of piles(KPa)
Equation (2) is more available for the case that the distance between any two protrusive disks are longer.

4. CONSTRUCTION AND THE SPECIAL EQUIPMENT

After the hole with the shape of column is formed, the special equipment, which is specially used to jam the soil and form the holes around the tooth blocks and under the tip of piles, is then placed. It forms two holes every time, which are symmetrical each other . If four holes on the same horizontal plane are needed, it can be easily completed by simply rotting the equipment over an angle of 90 degree. If more holes on the same plane are needed or a disk body is to be formed, one can rot the equipment over a required angle . The holes to the tooth blocks are formed by an order of up first and then down.

Finally the pile's heel and the loose earth are jammed. After the holes to all tooth blocks and the bottom disk body are formed, then the equipment is removed, and the concrete casts immediately. If required, reinforced cages or some structural rebars should placed before casting concrete.

5. CONCLUSION

1. The results from model tests showed that the bearing capacity of a MDJ pile is at least as three times as that of conventional filling piles. The degree of increment depends on the casting quality of the pile, the degree of jamming density of the soil, and the characteristics of the soil layers.

2. The MDJ pile can replace conventional piles with large diameters, and the consumption for material is much the less. If the new type pile be adopted, the volume of concrete may conserves 70% even more.

3. At present, the MDJ pile is the best of all kinds of piles used in treating foundation engineering. Due to its small settlement, a MDJ pile can be available to soft foundations and such engineerings that the settlement is strictly limited.

4. The MDJ pile is strong in pull-out resistance and shear resistance, and is an efficient kind of pile to resist earthquake. Furthermore, it is also effective in the engineerings such as oil tanks, large pools and docks, which has large floatage.

5. The tooth blocks at the pile's tip should changed into a protrusive disk. Some industrial inorganic gravels may be put under the pile's bottom, and be jammed in order that the bearing capacity of the new type piles be increased further.

6. The available number of tooth blocks on the same horizontal plane should not be more than four. The available distance between two planes not less than 1.5D (the diameter of the protrusive disk). When there only two tooth blocks on a plane, and the blocks on different planes are

arranged alternatively, the distance can shorted into half of the conventional one. All the blocks should be arranged alternatively on neighbour planes.

7. The results from the tests for three new type piles, the efficiency of pile No.4 is the best. Not only be the friction increased and the area of the supporting surface enlarged, but also the overlap of the compression stress in soil be avoided. In addition, the stability of piles is also increased.

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