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Static load test and load transfer mechanism study of squeezed branch and plate pile in collapsible loess foundation

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Abstract: As a special geological phenomenon, the character of collapsible loess foundation is collapsible when penetrated by water. This character leads to the soil losing load bearing capacity largely and may lead to foundation failure. Pile is a popular foundation used in collapsible loess. The squeezed branch and plate pile is a new type of pile developed in recent years and has not be used in a project before. In this paper three squeezed branch and plate piles are tested in collapsible loess after immersion processing. The results may be used for reference in similar construction project, and to provide theoretical references for designing of the squeezed branch and plate piles in engineering practice.

Key words: Collapsible loess foundation, Squeezed branch and plate pile, Immersion processing, Full-scale static load test
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INTRODUCTION

Pile is often designed to resist axial load acting on the pile head through the development of positive shaft resistance and end-bearing resistance. The traditional straight pile uses only the shaft skin resistance and the enlarged bottom pile uses only the end resistance provided by the bottom soil strata. To increase the single pile bearing capacity, many researchers tried many methods. For example, they add pile length, enlarge pile diameter, change the pile shape to enlarge surface of pile. But these methods add difficulty of construction, and increasing of bearing capacity may be limited. The squeezed branch pile is a kind of pile which has more than one enlarged part along the pile shaft based on the distribution of soil strata. The enlarged parts not only enlarge the pile surface but use the end bearing capacity of different soil strata under branches, plates and pile toe. So the bearing capacity of single pile may be increased and the settlement decreased. In fact, this kind of pile was used in India in the early 1940's and has proved to be an effective and economical solution to the problem of building foundations (Subhash and Khepar, 1964; Jain *et al*., 1969; Jain and Gupta, 1972), but it did not develop continuously for some unknown reasons. The squeezed branch pile was developed in China from the 1990's. Since then many researchers studied its load transfer mechanism. The squeezed branch and plate piles comprise an ideal form of undercut type footing, and are effective in anti-pulling as well as in resisting compression bearing (Qian, 2003). When using the hydraulic squeezed tool to squeeze the plates and branches, the soil around the pile is squeezed tightly at the same time. After the pile is completed, the concrete bonds with the soil tightly, the skin friction increases and pile bearing capacity is increased correspondingly. Many full size load tests and model tests were carried out and many theoretical investigations were performed. The results indicated that the single pile capacity increases compared to the popular straight pile of the

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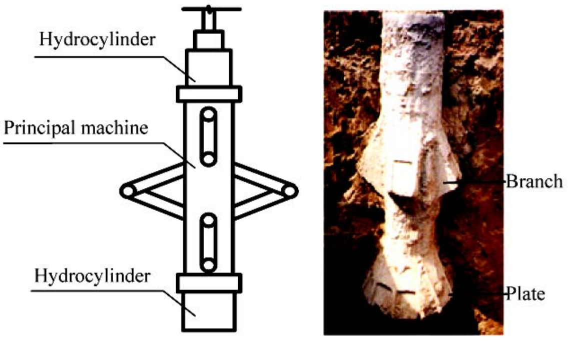
same diameter and length. The concrete bearing capacity of per cubic meter volume increases about 50% (Qian, 2004). At present, the squeezed branch and plate pile is used popularly in more than one hundred projects of more than ten provinces and results are satisfactory. Loess distributes over very large area in China. Pile foundations used in this type of soil comprise 20%~30% in all types of foundations. But there are few reports about squeezed branch and plate piles used in collapsible loess foundations, so, it is important to know the behavior of piles in this type of soil. This includes the ultimate bearing capacity and the settlement under working load, with the absence of a field test data on squeezed branch piles in collapsible loess foundations. A program of field tests on this type of piles was carried out at a site in Luoyang, Henan Province. Three field load tests were carried out to determine the bearing capacity of squeezed branch and plate pile in collapsible loess; all tests were carried out to failure. This paper presents and analyzes test results, with emphasis being placed on the ultimate bearing capacity and the settlement at working loads for the pile. The hydraulic squeezed tool is shown in Fig.1a and an excavated out branch and plate pile is shown in Fig.1b.



(a) (b)

Fig.1 (a) Hydraulic squeezed tool; (b) Excavated out squeezed branch and plate pile

PILE DATA AND SOIL CONDITION

The test site was in Luoyang City, Henan Province, where the soil is self-weight collapsible soil. The depth of collapsible strata is variable in different places. Under 300 kPa pressure, the collapsible depth is about 11.6~12.6 m. Field and laboratory tests were carried out for soil properties at different depths and the results are summarized in Table 1. Design parameters of test piles are summarized in Table 2.

OPERATION OF TEST AND ANCHOR PILES

Before the operation of squeezed branch and plate pile, static prospect test was carried out on site and groundwater was not encountered within the

Table 1 Distribution and physical properties of ground soil

Soil No.	Title	Depth (m)	Thickness (m)	ω (%)	e	ω_L (%)	ω_P (%)	I_L	I_P	Es_{1-2} (MPa)	f_{ak} (kPa)
1	Loess-like silty clay	8.5	8.50	8.6	1.040	26.4	16.9	−0.92	9.5	25.1	150
2	Loess-like silty clay	17.7	9.20	10.0	1.031	28.2	17.5	−0.72	10.7	27.9	170
3-1	Loess-like silty clay	19.2	1.5	9.3	0.961	28.2	18.0	−0.85	10.2	37.4	180
3-2	Loess-like silty clay	21.7	2.50	12.1	0.936	30.8	18.1	−0.52	12.7	31.6	190
3-3	Loess-like silty clay	23.2	1.50	12.4	0.939	29.0	18.4	−0.59	10.5	30.7	180
3-4	Loess-like silty clay	26.2	3.00	16.7	0.858	30.5	18.0	−0.19	12.5	20.0	185
3-5	Loess-like silty clay	27.5~30.1	1.30~3.90	14.8	0.724	27.3	17.1	−0.26	10.2	18.1	180
4	Loess-like silty clay	37.4~42.9	9.90~12.80	20.1	0.719	27.7	17.3	0.27	10.2	13.8	−
5-1	Loess-like silty clay	41.8~47.9	4.40~5.00	17.5	0.715	28.1	18.8	−0.14	9.4	14.9	−

ω=water content; ω_L=liquid limit; ω_P=plastic limit; e=void ratio; I_L=liquidity index; I_P=plasticity index; Es_{1-2}=modulus of compression; f_{ak}=standard value of strata bearing capacity

Table 2 Design parameters of test piles

Pile No.	Branch/plate No.	Plate (branch) size		Pile diameter (mm)	Pile length (m)	Pile length in soil (m)	Pile age (d)	Immersion time (d)
		Diameter (m)	Height (m)					
1	1/2	1.4 (1.2)	0.7	620	24.0	22.0	53	10
2	1/2	1.4 (1.2)	0.7	620	24.0	22.0	27	13
3	1/2	1.4 (1.2)	0.7	620	24.0	22.0	62	16

depth of the boreholes. Correct size and positions of plates and branch are important requirements in the construction of squeezed branch and plate piles and it should be ensured that the base has been enlarged to the correct diameter. To construct the squeezed branch and plate pile, a straight hole of 620 mm diameter was first bored to the design depth of 24 m, then the hydraulic squeezed tool was inserted into the hole to squeeze soil at the designed depth of branch and plate position. The plate first squeezed was the lower one along the pile shaft, whose diameter is 1400 mm and depth is 22.5 m. Then squeezed tool was exalted to 20 m along the hole to squeeze the top 1400 mm diameter plate. At last, the tool was raised to 11.5 m to squeeze the 1200 mm diameter branch. Reinforcement cage with stress gauges was put into the hole before concrete casting. The steel reinforcement must be lowered carefully so that it does not touch the sides, then, concrete was cast soon and pile was completed. For the anchor pile, the steel reinforcement cage was lowered into position after completion of the hole. Concrete was poured then through conduit to the top of the piles. The installation of all piles was carried out under favorable ground conditions. Construction progress of squeezed and plate pile is shown in Fig.2.

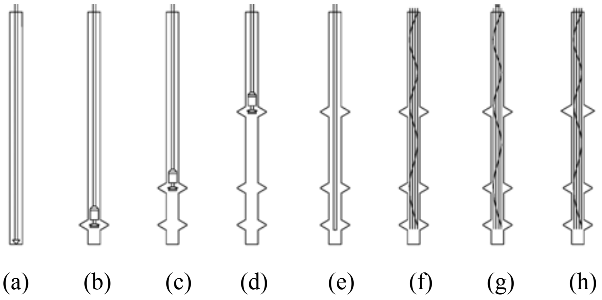


Fig.2 Sketch of construction progress of squeezed branch and plate pile

(a) Bore straight hole; (b) Squeeze the lower plate; (c) Squeeze the upper plate; (d) Squeeze the branch; (e) Clear hole; (f) Put the reinforcement cage; (g) Pour concrete; (h) Pile completed

EQUIPMENT OF STEEL STRESS GAUGES

To study axial load transfer mechanism, ten waterproofed steel stress gauges were attached to the two symmetrical reinforcing bars at depths of 2.0, 8.8, 13.2, 18.0 and 21.3 m as shown in Fig.3. The stress gauge wires, extending to ground level, were connected to a frequency indicator which reads frequency before and after the application of each load increment during the test. Using the steel stress gauge rating curve and concrete, steel strain coordinate relationship, the strain on pile section is calculated. Based on the locations of steel stress gauges, the pile was divided into five parts (from part 1 to part 5) from top to end. Shape of the test pile and positions of stress gauges are shown in Fig.3.

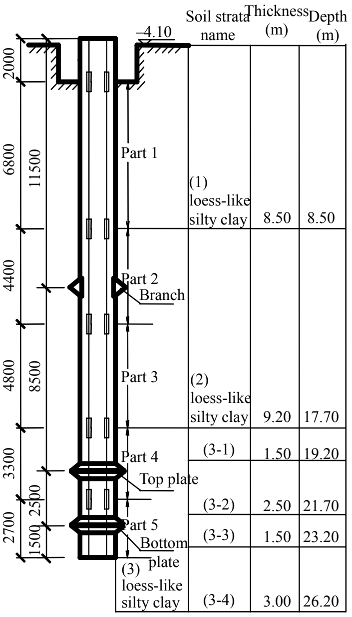


Fig.3 Position of steel stress gauges

ESTIMATE THE BEARING CAPACITY OF SINGLE PILE

Before static load test, the ultimate bearing capacity of pile is estimated. The ultimate bearing capacity of single pile is the sum of its skin friction and the end bearing capacity of the plates and branches and toe. Its value is estimated basing on Eq.(1) and the local experience.

$$Q = Q_{sk} + Q_{pk} = u\sum_{i=1}^{n} q_{sik} l_i + \sum_{j=1}^{n} \psi_{pj} q_{pjk} A_{pj} + q_{pk} A_p , \quad (1)$$

where Q is the ultimate bearing capacity of the pile; Q_{sk} is skin resistance of straight part i; Q_{pk} is bearing capacity of the sum of plates, branches and the pile toe; A_p is the cross-section area of the toe; u is perimeter of pile straight shaft; q_{sik} is standard value of skin resistance of soil stratum i; ψ_{pj} is plates and branches end bearing capacity factor; l_i is length of straight part i; q_{pjk} is standard value of end resistance of plate or branch j; A_{pj} is horizontal projection area of plate or branch j; q_{pk} is standard value of end bearing capacity of pile toe.

The design bearing capacity is 1300 kN for the three piles. The estimated ultimate bearing capacity of single pile based on Eq.(1) and local experience is 3000 kN, 3200 kN and 3200 kN for pile 1, pile 2 and pile 3, respectively. The total load is divided into ten equal grades for pile 1 and eight equal grades for pile 2 and pile 3 during the static load test.

LOAD TEST OF SINGLE PILE

Self-weight collapsible soil may settle seriously when it meets water, which may lead to failure of piles. To eliminate the collapsing of loess, immersion test was carried out. Firstly, four immersion boreholes of 200 mm diameter at 23 m depth were bored; coarse sand was filled into them. Then, 2.6 m diameter and 1.7 m depth sump was dug and 10 cm depth gravel was put at its bottom. Lastly, water was poured into the sump and water head was kept at 30 cm. Immersion time was not less than seven days, and 252 m^3 water was poured into the sump of each pile. Locations of penetration holes are shown in Fig.4. Locations of test piles and anchor piles are shown in Fig.5.

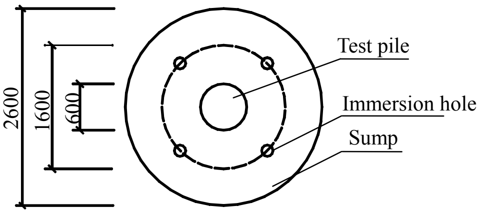


Fig.4 Locations of immersion holes (unit: mm)

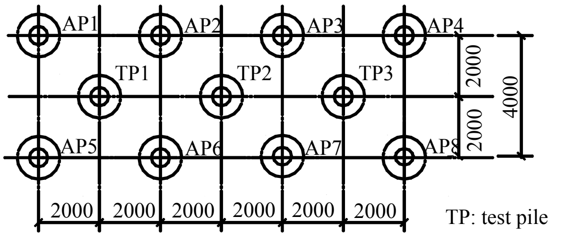


Fig.5 Locations of test piles and anchor piles (unit: mm)

After immersion test, low strain test was carried out. The results showed that all test piles and anchor piles were integrated and had no defects. Then static load tests were performed for three piles in a designated order. Instrumentation for the static load test included load test apparatus, data collection instrument, data save instrument and data output instrument. The displacement of the pile during the test was measured using two displacement sensors attached to an independent reference frame. Apparatus for the experiment is shown in Fig.6.

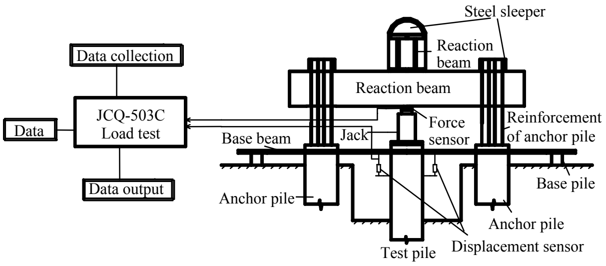


Fig.6 Apparatus for the experiment

Three axial load tests were carried out in February 2004. The vertical displacements of each pile were measured by three dial gauges having a range of 50 mm. To carry out a test, the load was applied in equal increments of 300 kN for pile 1 and 400 kN for pile 2 and pile 3. Each load increment was maintained for a time interval of not less than 15 min and until all displacements had ceased. The whole processing follows the technical code of building pile foundations. At each increment, dial gauge and stress gauge readings of instrumented piles were taken. All the three piles in this database were tested up to failure. The safety factor 2 is allowed on the ultimate capacity for the design of piles, so when the design bearing capacity of single pile is 1300 kN, the load added on the pile top must be more than 2600 kN. Table 3 is a summary of the bearing capacity of a single pile and corresponding settlement.

It is clearly to see that the ultimate bearing capacity is 3600 kN, 3200 kN, 3200 kN and that allowable bearing capacity is 1800 kN, 1600 kN, 1600 kN for pile 1, pile 2 and pile 3, respectively. The real ultimate bearing capacity is 2.77, 2.46, 2.46 times that of design bearing capacity, respectively. The safety factor was more than 2, so the piles are safe under working load. Under working load, the pile top settlement was 3.09 mm, 2.84 mm, 3.09 mm. The safety factor was so large and the settlement so small that the squeezed branch and plate pile is a good type foundation for some important buildings which require very little settlement.

Table 4 is a summary of side resistance and pile toe resistance measured by static load test. Based on the requirements of technical code of building pile foundations, the ultimate bearing capacity is intended to be 3600 kN, 3200 kN, 3200 kN. The bearing capacity is made up of skin resistance and end resistance, with end resistance content being about 79.1%, 75.7%, 75.1% of the total load, respectively. The skin resistance content was less than 25% the total load for the three piles. Load shared by branch and plates are far more than the straight part and pile toe. So the ultimate bearing capacity is higher than that of the straight pile.

ANALYSIS OF STATIC LOAD TEST RESULTS

Load versus settlement for single pile

The test processing is controlled by settlement of pile top, the load test is terminated once the pile head displacement exceeds 40 mm or an inflexion point appears on the Q-s curve and ultimate bearing capacity can be definite. The load-settlement curves for the piles are shown in Fig.7. As expected, the pile displacement increases with applied load. When the settlement is less than 5 mm, the curve is almost linear for each pile. After settlement exceeding 5 mm, the curve is nonlinear. When piles are under working load, the settlements were less than 5 mm and the piles were safe (Gao and Zhu, 2006).

Axial load transfer along the pile shaft

Axial load transfers along the three piles' shaft are shown in Fig.8. The data points in Fig.8 were determined from the steel stress gauges reading at each level. $Q_i=E_p\varepsilon_iA_P$ (where Q_i=axial load of cross section i, E_p=Young's modulus of pile, ε_i=strain of cross section i, A_p=cross section area of pile).

The load was obtained from the stress reading at each level multiplied by the transformed area. Fig.8 shows that the load decreases quickly from pile top to toe because of the existence of the plates and branches. For example, under the first load grade, the load transferred to part 5 is 5.1%, 3.8%, 3.0% of the total load, respectively. With the top load increasing, the load transferred to part 5 increases quickly. Under the ultimate load, load shared by part 5 of three piles is 20.9%, 24.3%, 24.9%, respectively. When more load was added on the pile, load transferred to part 5 increased significantly. Under the maximum load, part 5 shared 32.9%, 36.2%, 33.1% of the total load for the three piles.

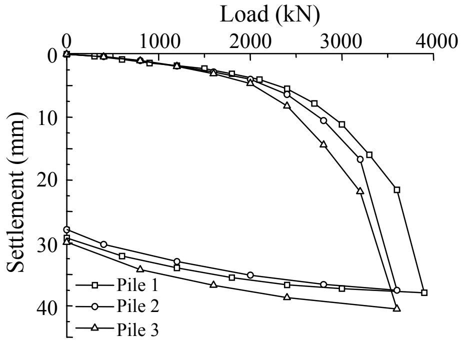


Fig.7 Relationship between load and settlement

Table 3 Bearing capacity and corresponding settlement of single pile

Pile No.	C_r (kN)	P_{max} (kN)	S_{max} (mm)	P_u (kN)	S_u (mm)	C_t (kN)	S_w (mm)
1	1300	3900	37.89	3600	21.55	1800	3.09
2	1300	3600	37.50	3200	16.73	1600	2.84
3	1300	3600	40.51	3200	21.83	1600	3.09

C_r: required bearing capacity; P_{max}: maximum load; S_{max}: maximum settlement; P_u: ultimate load; S_u: settlement under ultimate load; C_t: test bearing capacity; S_w: settlement under working load

Table 4 Skin and end resistance measured by static load test

Pile No.	C_{sp} (kN)	R_{uts} (kN)	R_{ute} (kN)	F_{us1} (kPa)	F_{us2} (kPa)	F_{ue} (kPa)	P_{ue} (kN)	PL_{pt} (%)	PL_{ps} (%)
1	3600	754	2846	43	50	490	148	4.1	95.9
2	3200	777	2423	37	48	505	153	4.8	95.2
3	3200	797	2403	36	45	518	156	4.9	95.1

C_{sp}: bearing capacity of single pile; R_{uts}: ultimate total skin resistance; R_{ute}: ultimate total end resistance; F_{us1}: ultimate skin friction of stratum 1; F_{us2}: ultimate skin friction of stratum 2; F_{ue}: ultimate average end resistance of pile toe; P_{ue}: ultimate end resistance of pile toe; PL_{pt}: percentage load shared by pile toe; PL_{ps}: percentage load shared by pile side

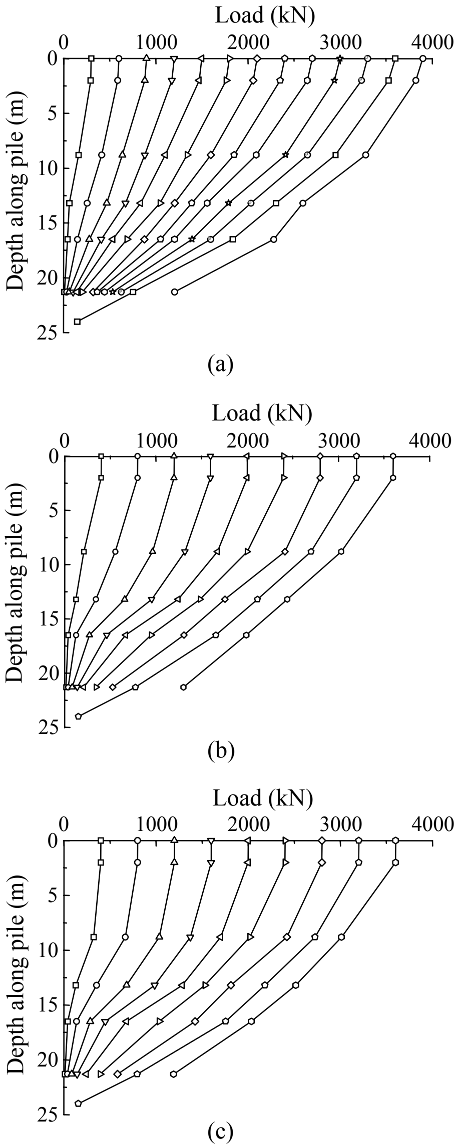


Fig.8 Axial load transfer curve of single pile
(a) Pile 1; (b) Pile 2; (c) Pile 3

Under working load, the proportion of end resistance of three piles was 56%, 52%, 42% of the total load. Under ultimate load, this proportion increased to 71%, 70%, 70%. Based on the high strain test result, the load transferred to the pile toe was 148 kN, 152 kN, 156 kN, which was 4.1%, 4.8%, 4.9% of the total load at this time. So, except for the load transferred to the pile toe, the branch and two plates shared 66.9%, 65.2%, 65.1% of the total load; the skin resistance shared only approximately 30% of the total load at this time. If the load shared by the pile side is considered friction capacity, the squeezed branch and plate pile is friction pile. If the loads shared by branch, plates and pile toe are considered end capacity, the pile may be friction-end bearing pile.

The load test result also indicated that when the pile reached to the ultimate bearing capacity, the load shared by bottom plate is 56.0%, 70.9%, 66.8% that of the top plate. That is to say, the top plate shares more load than bottom plate. The two plates are in two similar soil strata and should have similar bearing capacity under the ultimate bearing capacity. This result indicates that the bearing capacity of the bottom plate cannot be brought into play even under ultimate load (Lu *et al.*, 2004). So, to use the soil bearing capacity more fully and save more construction cost, the plates especially top plate should be placed in soil strata with relatively high bearing capacity and top plate should be larger than bottom plate in future designing (Gao and Li, 2005).

Static resistance distribution along the pile shaft

As well known, negative skin friction will develop whenever the adjacent soil settles more than the pile. The negative skin friction along the pile shaft is a very important problem for the designing of pile foundation in collapsible loess. The magnitude of downdrag can be quite significant and may lead to pile failure if it was not considered sufficiently during design processing.

In this paper, negative skin friction did not appear during the static load test. Perhaps because the strata had no high compressibility and the soil strata had relatively high bearing capacity where the branch and two plates located in. And also perhaps because the corresponding position soil strata were squeezed tightly and soil bearing capacity increased, and immersion processing eliminated the collapsing of loess.

Relationship between load percentage of every part and settlement of pile top

Relationship between load percentage shared by part 1 to part 5 and settlement of pile top is shown in Figs.9 and 10. It is clearly to see from Fig.9 that at the beginning of test, part 1 shared most of the load and part 3 shared less load than part 1. With the increasing of total load, load percentage shared by part 1 decreased quickly, part 3 increased first and then decreased and later almost kept a steady state to last. A peak value appeared when the settlement was 1.81

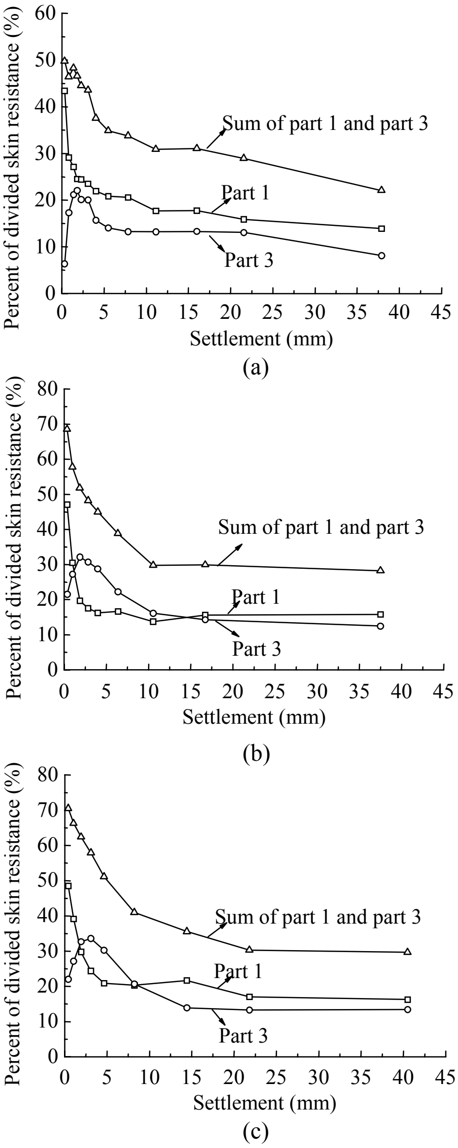


Fig.9 Relationship between load percentage shared by two straight parts and pile top settlement
(a) Pile 1; (b) Pile 2; (c) Pile 3

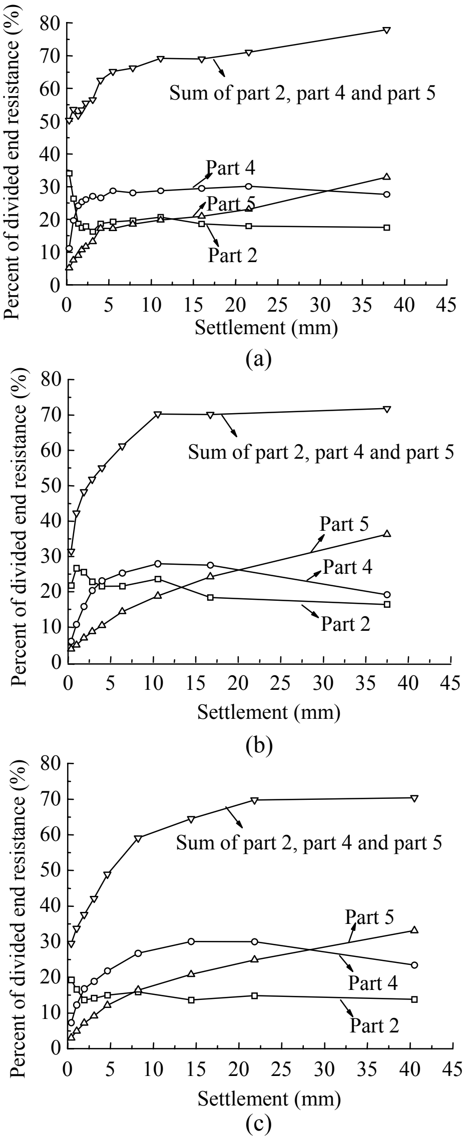


Fig.10 Relationship between load percentage shared by three parts with branch or plate and pile top settlement
(a) Pile 1; (b) Pile 2; (c) Pile 3

mm, 1.87 mm, 3.09 mm for the three piles, and corresponding load percentage was 22.1%, 32.1%, 33.6%, respectively. Because decreasing speed of part 1 was larger than increasing speed of part 3, the curve of sum part 1 and part 3 kept decreasing and then reached a relatively steady state.

Fig.10 indicates that part 2 almost kept a decreasing trend from the beginning of the test and later reached to a relatively steady state, only pile 2 had a little increase at first. Part 4 increased first and then almost kept a steady state till the test ended for pile 1. For piles 2 and 3, a peak value appeared at each curve. It is at the settlement of 21.55, 10.55, 14.43 mm, and corresponding load percentage was 30.1%, 27.9%, 30.0%, respectively. Part 5 increases steadily till the last for three piles. Because the increments of parts 4 and 5 are larger than the decrement of part 2, the sum load percentage of those three parts increased first and later kept almost steady. Curves shown in Figs.9 and 10 indicate that load transfer process for squeezed branch and plate pile is very complicated because of existence of branches and plates.

CONCLUSION

The following conclusions may be drawn from this study:

(1) This test is an example of squeezed branch and plate pile used in collapsible loess. The safety factor was 2.77, 2.46, 2.46 for the three piles, as the piles settlement were small the piles were safe under working load.

(2) The field tests carried out in this program revealed important information with respect to the behavior of squeezed branch and plate pile. Negative skin friction did not appear in those static load tests, perhaps because the soil around branch and plates was squeezed tightly, and the immersion processing eliminated the collapsibility of loess.

(3) Bearing capacity of single squeezed branch and plate pile is made up of skin and end resistance, total skin resistance decreased and total end resistance increased first, and then reached a relatively steady state. Branch and plates share most loads and the load transfer to the pile toe was very low.

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