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Lab Model Test of Laterally Restrained Sand Pile

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Abstract: Lab model test has been one of the most important methods to study the reinforcement mechanism of composite foundation and the effect of reinforcement to foundations of this type. In light of the interaction mechanism, the author creates several model sand piles by making closed cylinder molds with 70g standard A4 paper (or newspaper) as the packing material, and then fill in the inside of the cylinder molds with separate layers of sand. Similar to the way inter-pile soil laterally restrains sand pile in a composite foundation, the cylinder molds apply lateral restraining force on the sand inside. For the purpose of verifying the reasonability of the model pile and exploring how the strength of the packing material, the compacted density of the filler, and the sectional area of the confinement impact the vertical bearing capacity of the model piles, the author conducts loading tests on the model piles with a self-designed lab loading device and compares the results with those generated from similar tests performed with a loading press. The results show that the vertical bearing capacity of sand piles could be significantly improved by applying lateral restraining force within a certain range on the top of the pile; the strength of packing material determines whether the model sand piles would end up in buckling or bulging failure, the vertical bearing capacity of the model piles increase with the mean compacted density of the packing material, and the sectional area of the confinement indicates the magnitude of the restraining force exerted from the packing material upon the filler inside, which not only affects the bearing capacity but also the failure location of sand piles.

Keywords: *model pile, lateral restraint, model test, confinement, failure mode*

1. Introduction

Originated in Europe in the 1930s, the sand compaction pile method (SCP) was introduced to China in the 1950s. The method brings excellent social and economic benefits as it helps to reinforce foundations on saturated soft soil in the southeastern coastal areas of China[1]. SCP is mostly used on foundations on loose sandy soil and unsaturated clayey soil with a low plasticity index. Thanks to its simple procedures, low cost, good reinforcement effect and pollution-free effect, the method has been widely used in the construction of China's industrial and civil buildings[2], transport infrastructure[3] and water conservancy facilities[4] over the last decade. Much research has been done on SCP by scholars at home and abroad. Malarvizhi and Ilamparuthi (2004)[5] performed loading tests of stone column with different support conditions, various slenderness ratios and external reinforcement so as to identify effects on the settlement. Raithel and Kirchner(2008)[6] proposed an analytical model for numerical analysis approach of geotextile-encased columns and its application to the dam foundation. Afterwards, various researchers performed experimental and numerical works on the geotextile encased sand or gravel (or crushed stone) piles and characterize the compressive strength, load-settlement relationship and creep behaviors[7-11]. Yoo et al (2015)[12] performed the characteristics of mechanical behaviors such as bearing capacity and stress concentration ratio of a composite ground improved using the conventional Sand Compaction Piles (Sand Compaction Pile, SCP)s reinforced with geotextile (Geotextile-Encased Sand Pile, GESP) as an alternative to the conventional SCP method. In China, Zhao et al. (2003)[13] explore into the combined effect and reinforcement of multiple gravel piles under highway embankment through the lab model test of gravel pile composite foundation. Dong et al. (2005) [14] examine various factors affecting the settlement of composite foundation through numerical simulation. Wang et al. (2007) [15]carry out lab model test of multi-sand pile composite foundation and discover that the reinforcement effect is the best when sand piles are used to treat fine sandy soil. Zheng et al. (2008) [16]study multi-element composite foundation with steel pipe piles and sand piles, concluding that such a foundation apparently outperforms sand pile composite foundation on fine sandy soil. After comparing composite foundations with a single sand pile, multiple sand piles, and steel pipe pile in a lab model test, Zhu et al. (2013) [17]draw the conclusion that steel pipe pile has a weak bearing capacity and obvious stress concentration on the top, while composite foundation with multiple sand piles, featuring small total settlement, strong bearing capacity, and significant pile displacement, fully unlock the bearing capacity of inter-pile soil. Although the above-mentioned scholars have made useful research on the effect, bearing capacity and settlement of sand-pile composite foundation through lab model test, little research has been published on how the bearing capacity and failure mode of sand pile would change after lateral restraints are artificially applied to the surroundings (confinement) of the sand pile. That's why this paper explores the impact of confinement to the bearing capacity of sand pile. To carry out the lab model test, the author creates several model sand piles by making closed cylinder molds with 70g standard A4 paper (or newspaper), and then fill in the inside of the cylinder molds with separate layers of sand. Similar to the way the surrounding soil laterally restrains sand pile in a composite foundation, the cylinder molds apply lateral restraining force on the sand inside. After dead-load tests on the model sand piles, the author draws some beneficial conclusions.

2. Test Plan

2.1 Creation of Laterally Restrained Model Sand Pile

According to field tests and theoretic analysis, without the confinement effect of surrounding soil, it's impossible for sand pile and other reinforcement made of discrete materials to maintain its shape or provide vertical bearing capacity. Subjected to bulging deformation under the action of load, such reinforcement relies on the passive earth pressure from the surrounding soil to offset the upper load and maintain the balance of the pile. In other words, the vertical bearing capacity of the reinforcement depends on the lateral restraining force exerted by the surrounding soil, or more precisely, on the shearing strength of the surrounding soil. Therefore, the model test uses closed cylindrical molds made of standard A4 paper (or newspaper) with the hollow part of the cylindrical molds filled with sand to form a model pile. The cylindrical material acts as a confinement, applying lateral restraining force to the sand piles, similar to the lateral restraining force radially applied by inter-pile soil on sand pile in a composite foundation.

To create model sand piles, the author folds 70g standard A4 paper into closed cylinder molds with diameters of 20mm, 30mm and 40mm. The sheet of A4 paper is rolled 2 laps lengthwise to form a paper cylinder twice as thick as the paper. Then, the hollow part of the cylinder is filled with sand. The sand is poured into the mold layer by layer with each layer compacted before a new layer of sand is poured in. In order to compare the restraining effect of confinements with varied strength, the author also makes several molds with newspaper. The newspaper is rolled 2 laps in print direction to form a paper cylinder twice as thick as the newspaper. Then, the hollow part of the cylinder is filled with dry sand with grain size between 1mm and 2mm, and internal friction angle of 33°.

2.2 Lab Loading Device for Sand Piles

The author develops a loading device for the loading tests on model piles. Figure 1 displays the structure of the device. It's mainly made up of a stand, a load generator, and a compressive deformation measuring system. The load generator consists of weights of known mass, the measuring system consists of a settlement measuring plate and a dial indicator, and the stand consists of retaining columns and retaining plates.

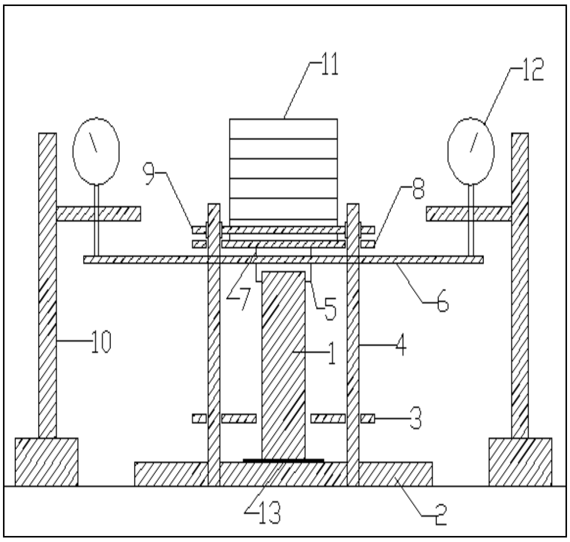


Figure 1: *Model Pile Loading Device*

1.Sand pile; 2. Base plate; 3. Lower retaining plate; 4. Column; 5. Pile cap; 6. Settlement measuring plate; 7. Cushion block; 8. Loading plate; 9. Upper retaining plate; 10. Dial indicator holders; 11. Weights; 12. Dial indicators; 13. Double faced adhesive tape

2.3. Dead-load Test

2.3.1 Preparations

Fix the cylindrical mold made of A4 paper on the base plate with double faced adhesive tape. Divide the cylindrical mold into several 10mm-deep layers. Pour sand into the mold layer by layer, and compact each layer before pouring in a new layer of sand. When sand reaches the top of the pile, a model pile is created. After that, let the model pile sit for 20mins. In accordance with Figure 1, install the retaining plate below the column, pile cap, settlement measuring plate, cushion block, loading plate, and the retaining plate above the column one after another, meanwhile ensuring that the model pile lies in the geometric center of the load plate. Then, fix dial indicators on the holders at both sides of the settlement measuring plate.

2.3.2. Loading and Measurement

Two loading methods are used. In the first method, the loading device shown in Figure 1 is used. Weights are artificially added to generate load for the dead-load test (hereinafter referred to as manual loading). The loading method is adopted in reference to Appendix C, *Technical Code for Ground Treatment of Buildings*(JGJ79-2012). [18] Put 1,275g on stage 1, and add an extra 636g on each stage. In each test, keep loading till the model pile fails. In the meantime, record the readings on dial indicators at both sides of the settlement measuring plate to measure the compressive deformation at the top of the pile.

The second method is press loading. The press model is ETM-504C. During the loading process, apply displacement control, and control the loading speed at 5mm/min.

2.3.3. Test Groups

9 groups are designed based on parameters like pile length, pile diameter, confinement material and loading mode. Each group is tested at least three times in parallel.

Table 1: *Test Groups for Laterally Restrained Sand Pile*

Test Group	Pile Diameter/mm	Pile Length/mm	Packing Material	Loading Mode
A	20	60	A4	Manual
B	20	80	A4	Manual
C	20	100	A4	Manual
D	30	100	A4	Manual
E	40	100	A4	Manual
F	30	100	Newspaper	Loading Press
G	40	100	Newspaper	Loading Press
H	30	100	A4	Loading Press
I	40	100	A4	Loading Press

3. Model Test Results

Through the test, the author obtains the stress-compressive deformation curves of 9 groups of model piles (from Group A to Group I). The pile diameter is changed from 20mm, 30mm to 40mm, and the pile length is changed from 60mm, 80mm to 100mm. Each time, the author keeps loading till the model pile fails. The stage of loading preceding the failure is recorded at the end of the loading curve.

The ultimate stress of model piles varies greatly for the average value scattered between 129kPa and 1,349kPa. In any of the 3 parallel tests for each group of sand pile, the range of ultimate stress always stays below 30% of the average ultimate stress, which is consistent with the requirements in the *Technical Code for Ground Treatment of Buildings*(JGJ79-2012). [18]

In light of the grouping in Table 1, the author carries out loading tests for model piles from Group A to Group I, and 3 parallel tests for each group, thus generating Stress-Compressive deformation Curves (1) to (9) in Figure 2. The parameters related to the test curves are recorded in Table 2. Classified by pattern types, the curves fall into the following 4 categories:

The first type of curves, e.g. the curves of Groups A, B & C, is convex fold lines. Each curve begins with a straight segment, which demonstrates the compaction process. On this stage, the author compacts the filler inside the model piles. After the inflection point, the stress and compressive deformation increase linearly due to the lateral restraint from the cylindrical mold. The vertical bearing capacity of the model pile keeps increasing until the buckling failure. See Curves (1) to (3) in Figure 2.

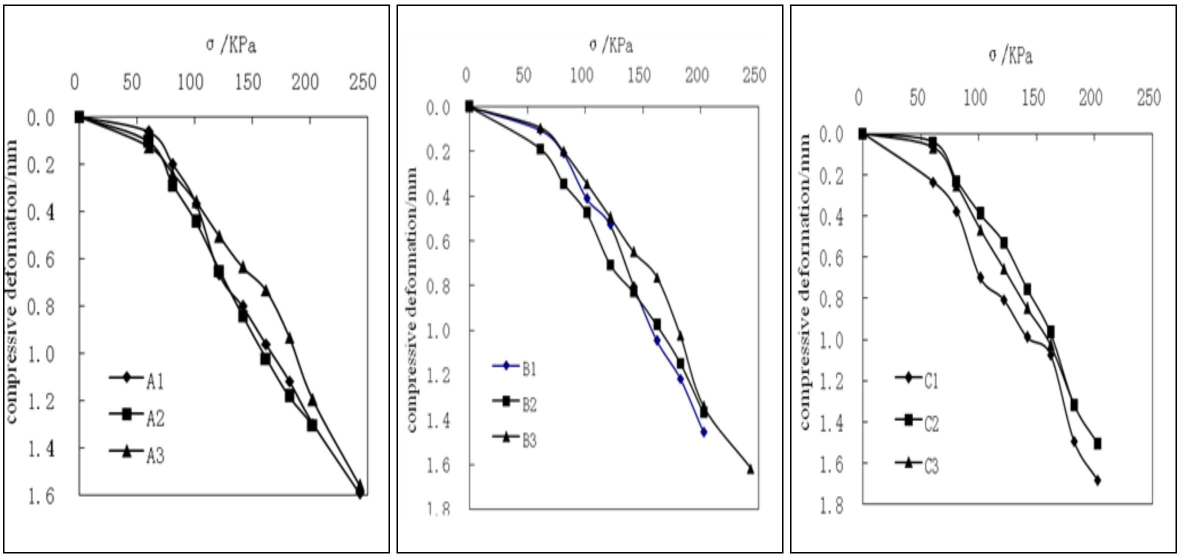
Similar to the first type, the second type of curves, e.g. the curves of Groups D & E, is also convex fold lines. But after the inflection point, the lines bend slightly, signifying plastic deformation on later stage of loading. The bend is possibly attributable to the lower compacted density of the filler in Groups D&E. According to Table 2, the compacted density of the two groups is respectively 1.52g/cm^3 and 1.54g/cm^3, far below that of other groups. After initial loading, due to the restraint from packing materials, the compaction of the filler is slowed down when the pressure moves downward. That's why the curve reflects a certain degree of plastic deformation. See Curves (4) to (5) in Figure 2.

The third type of curves, however, is of S-shape, e.g. the curves of Groups F&G. For these curves, linear compaction occurs at the onset, followed by plastic bending, and linear increase of stress and compressive deformation. At the final stage, due to the lateral compression of the packing material to the model pile, the packing material undergoes plastic deformation and eventually bulging failure. The plastic failure is represented by the downward bend on the curves. See Curves (6) to (7) in Figure 2.

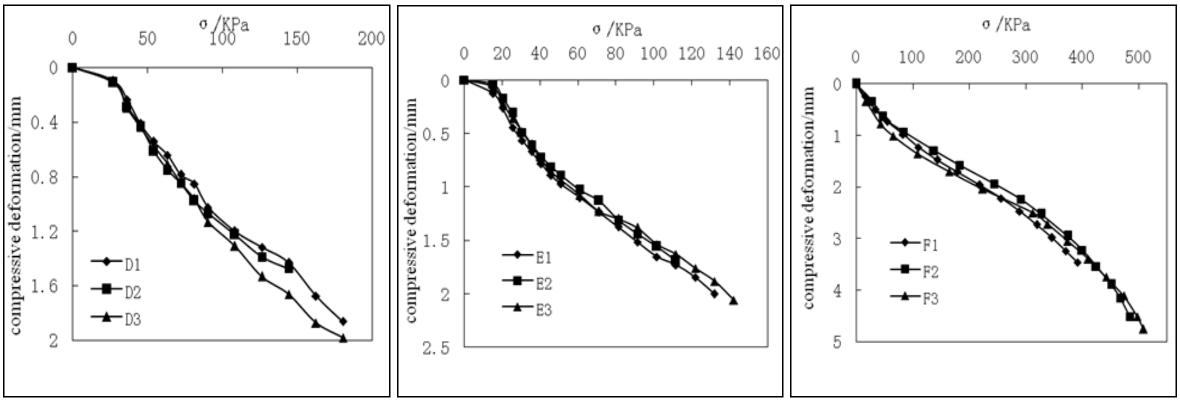
The fourth type of curves is concave fold lines, e.g. the curves of Groups H & I. The pattern may have something to do with the strength of the packing materials and the loading method. Since press loaders are used for Groups H & I, the loading is continuous and fast. This type of curves bears resemblances to the first half of S-curve, or the third type of curves. Moreover, the model piles reflected by the third type of curves are packed in newspaper, while those in Groups H & I are packed in A4 paper instead. The two packing materials differ greatly. A single sheet of A4 paper has a tensile strength of 3N/mm, much higher that of a single sheet of newspaper, which is just 2.3N/mm. Under the same tensile stress, A4 paper has less strain. See Figure 3. A4 paper model piles only suffer from buckling failure. No bulging failure ever occurs. That is to say, the strength of the packing material is not damaged. See relevant discussion in Section 4.4. Therefore, the second half of this type of curves do not show any obvious downward bend caused by damaged tensile ductility of the packing material, but a sudden buckling failure. See Curves (8) to (9) in Figure 2.

Table 2: *Parameters of Stress-Compressive Deformation Curves of Each Group of Models Piles*

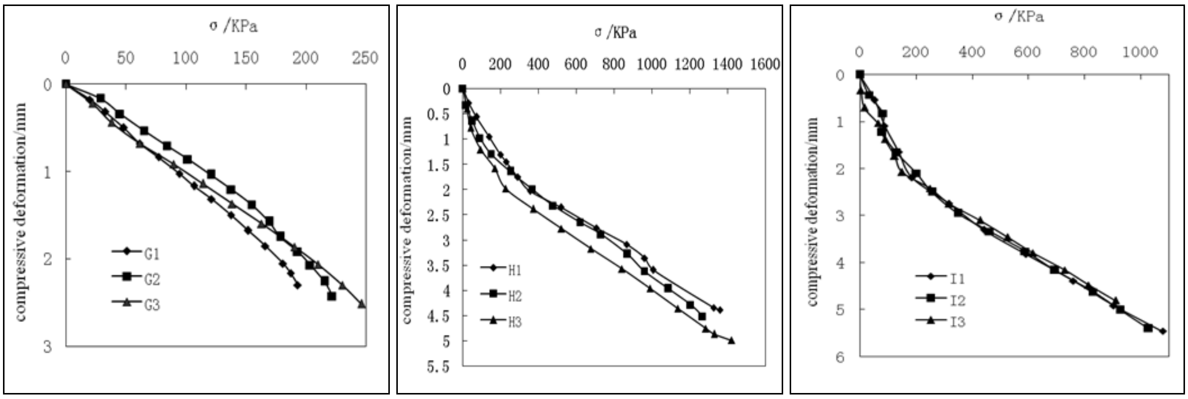
Test No.	Pile Diameter /mm	Pile Length /mm	Ultimate Stress /kPa	Settlement /mm	Compressed Density /g·cm^{-3}	Range /Average Value	Ultimate Stress /kPa	Average Compacted Density /g·cm^{-3}	Failure Location /mm	Failure Location Pile Diameter Ratio	Failure Mode
			243	1.59	1.62						
A	20	60	202	1.30	1.61	17.6%	229	1.62	21.2	1.1D	Buckling
			243	1.56	1.62						
			203	1.46	1.61						
B	20	80	203	1.37	1.61	18.7%	216	1.61	26.2	1.3D	Buckling
			243	1.62	1.62						
			203	1.68	1.60						
C	20	100	203	1.50	1.59	10.4%	196	1.59	36.7	1.8D	Buckling
			183	1.32	1.57						
			180	1.86	1.52						
D	30	100	144	1.47	1.51	21.4%	168	1.52	40.9	1.4D	Buckling
			180	1.98	1.53						
			132	2.00	1.54						
E	40	100	112	1.69	1.51	23.7%	129	1.54	20.5	0.5D	Buckling
			142	2.06	1.55						
			391	3.46	1.59						
F	30	100	484	4.51	1.60	25.3%	461	1.60	40.8	1.4D	Bulging
			509	4.76	1.61						
			193	2.30	1.61						
G	40	100	222	2.43	1.61	24.1%	220	1.61	31.5	0.8D	Bulging
			246	2.51	1.62						
			1359	4.38	1.61						
H	30	100	1267	4.51	1.59	11.3%	1349	1.60	35.3	1.2D	Buckling
			1420	4.99	1.61						
			1079	5.46	1.62						
I	40	100	1029	5.40	1.61	16.7%	1006	1.61	32.4	0.8D	Buckling
			911	4.80	1.59						



(1) Group A ***(2) Group B*** ***(3) Group C***



(4) Group D *(5) Group E* *(6) Group F*



(7) Group G *(8) Group H* *(9) Group I*

***Figure 2**: Stress-compressed deformation curves of model pile loading tests*

4. Discussion

4.1. Influence of the Strength of Packing Material on the Bearing Capacity of Model Piles

Firstly, make a comparison between piles in Groups F, G, H & I. These piles are all 100mm long, and loaded in the same manner, that is with a loading press. Specifically speaking, the model piles in Group F (30mm in diameter) and Group G (40mm in diameter) are packed in newspaper, while those in Group H (30mm in diameter) and Group I (40mm in diameter) are packed in A4 paper. The curves of packing material tensile test are displayed in Figure 3. The ultimate tensile strength of a single sheet of thick newspaper is 2.3N/mm, and that of a single sheet of thick A4 paper is 3N/mm. The packing materials are rolled into a cylinder twice the thickness of A4 paper or newspaper. If the cylinder is made of A4 paper, the tangential tensile strength of the circumference is 6N/mm; if the cylinder is made of newspaper, the tangential tensile strength of the circumference is 4.6N/mm. Hence, the newspaper has a far weaker tensile strength than A4 paper.

Secondly, make a comparison between Group F and Group H. The two groups remain consistent on pile diameter (30mm) and the average packing density of the filler (1.60g/cm^3), but differ on the average ultimate stress at the top of pile, 461kPa and 1,349kPa respectively, marking a 3 times increase in bearing capacity. Likewise, make another comparison between Group G and Group I, both of which are made up of 40mm-diameter piles. In these two groups, the average ultimate stress at the top of pile is respectively 220kPa and 1,006kPa, marking a 4.6 times increase in bearing capacity. See Table 2. It can be seen that, with the increase of the tensile strength of the packing material, the average ultimate stress at the top of the pile is remarkably increased. Therefore, for sand piles in soft soil, the vertical bearing capacity can be significantly improved by applying artificial lateral restraint on sand piles. This provides a new idea for the design of sand pile composite foundation.

4.2. Influence of Packed Density on the Bearing Capacity of Model Piles

The compressive density of the packing material has a certain influence on the vertical bearing capacity of model sand piles. As shown in Table 2, when the pile diameter and pile length are the same, the vertical bearing capacity of model piles varies with the compacted density of the filler. For example, in Group A, the three piles in parallel tests have the same diameter (20mm) and length (60mm), but differ on packing density, which is 1.62g/cm^3, 1.61g/cm^3 and 1.62g/cm^3 respectively. The corresponding ultimate stress grows with the compacted density, standing at 243KPa, 202KPa and 243KPa respectively. The parallel tests of other groups show the same variation pattern, such as the three piles in Group F.

The influence of pile length on the vertical bearing capacity of model piles is not as significant as that of the packing material. Take Group D and Group E as an example. Because of low compacted density during pile making, the average compacted density of these two groups is 1.52g/ cm^3 and 1.54g/cm^3 respectively, far below the average density of 1.59g/cm^3 in Group C. In spite of the same pile length (100mm), the bearing capacity of Group D, E & E changes from 168kPa, 129kPa to 196kPa. The vertical bearing capacity of model piles in Group D and Group E lags behind that in Group C by 14.3% and 34.2% respectively. The gap is not caused by the change of pile length, but the result of the difference in compacted density.

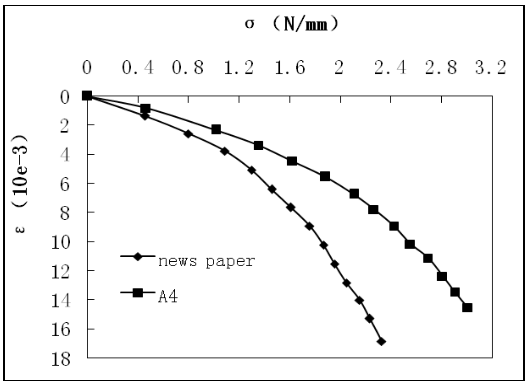


Figure 3: *Stress-Strain Curves of Packing Materials*

Then, make a comparison between Groups A, B & C. The three groups have the same diameter (20mm), but differ on average compacted density of the filler, which is 1.62g/cm^3, 1.61g/cm^3 and 1.59g/cm^3 respectively. The corresponding ultimate stress grows with the compacted density, standing at 229KPa, 216KPa and 196KPa respectively. With reference to the foregoing analysis, the drop in vertical bearing capacity of model piles is not caused by the change of pile length, but the result of the difference in average compacted density of the filler.

4.3. Influence of the Sectional Area of the Confinement on the Bearing Capacity of Sand Piles

The so-called sectional area of the confinement is actually the sectional area of the filler of model piles. The sectional area can be expressed by pile diameter, but the two terms bear different meanings. The sectional area of the confinement represents the strength of restraint from the packing material on the filler inside, while pile diameter only denotes the sectional area of sand piles. The variation in the sectional area of the confinement is described with pile diameter in the following analysis. The sectional area of the confinement has a great influence on the vertical bearing capacity of the model piles. For example, Groups C, D & E have the same packing material (A4 paper) and the same loading mode, but differ on pile diameter, which is 20mm, 30mm and 40mm respectively. The corresponding ultimate stress stands at 196kPa, 168kPa and 129kPa respectively. The vertical bearing capacity of model piles in Group D and Group E lags behind that in Group C by 14.3% and 34.2% respectively. The average compacted density of the two groups stands at 1.52g/ cm^3 and 1.54g/cm^3 respectively. According to the analysis in section 4.1 above, the vertical bearing capacity of model piles increase with the increase of compaction density. Nevertheless, since Group D and Group E feature an average ultimate stress at 169kPa and 129kPa respectively, the variation of vertical bearing capacity of model piles fails to meet the rule of increasing with the compacted density. Hence, the difference of bearing capacity should not be attributed to the compacted density of the filler. Except for the sectional area of the confinement, Groups D, E & C share the same external conditions. Therefore, the only possible cause of the difference is the variation in the sectional area of the confinement. During the loading process, the loading plate exerts loads on the filler and packing materials of model piles simultaneously. In the form of a thin plate, the packing material can provide some support. The smaller the sectional area is, the higher the vertical stiffness, and the more unlikely for the confinement to buckle. On the contrary, the larger the sectional area is, the smaller the vertical support provided by the packing material, and the more likely for the confinement to bend. As the curvature of the wrapping material changes, the rigidity is different. The smaller the sectional area of the confinement is, the higher the bearing capacity of the model piles.

Next, the author compares Group F and Group G. The two groups have the same packing material (newspaper), the same pile length (100mm), and the same loading mode (with a loading press), but differ on pile diameter (30mm and 40mm respectively) and the average compacted density, which is 1.60g/cm^3 and 1.61g/cm^3 respectively. Group F has a slightly higher compacted density than Group G. In accordance with the variation pattern that the vertical bearing capacity of model piles increase with the increase of compaction density, Group F should feature a higher vertical bearing capacity than Group G. However, the corresponding average ultimate stress of the two groups is respectively 461kPa and 220kPa. Due to the reduction of the sectional area of the confinement, the average ultimate stress of Group F is more than double of that of Group G. For the same reason, the average ultimate stress of Group H and Group I, both of which are packed in A4 paper, is 1,349 kPa and 1,006 kPa respectively. The average ultimate stress of Group H exceeds that of Group I by 34%. It can be seen that, when the packing material and the filler are simultaneously loaded, the variation in the sectional area of the confinement still has a significant impact on the vertical bearing capacity of the model piles. The impact must be taken serious in the design of model piles.

4.4. Failure Modes of Laterally Restrained Sand Piles

For piles made of discrete materials, the ultimate bearing capacity is mainly determined by the maximum lateral force of the soil on the side of the pile. Under the action of the load, the pile body expands and the soil around the pile enters the plastic state, and gradually shifts to the ultimate state with the plastic zone expanding. The ultimate bearing capacity of single pile can be obtained by calculating the lateral ultimate stress of inter-pile soil.

The general expression of ultimate load capacity (P_{pf}) of sand piles is:

$$P_{pf}=\sigma_{ru}K_p \tag{1}$$

Where: σ_{ru} refers to the maximum lateral force of the soil on the side of the pile, kPa; K_p refers to passive earth pressure coefficient of discrete materials.

In the design of the model piles, the cylindrical mold is made from thin plate materials. The cylindrical mold provides the lateral restraining force to the discrete materials filled inside. It acts as a confinement, similar to the lateral restraining force applied by inter-pile soil on sand pile in a composite foundation with reinforcement made of discrete materials. During the tests, the cylindrical mold and the filler are simultaneously loaded without giving consideration to the deformation of the surrounding soil or the influence of the surrounding soil on vertical deformation during the loading process. As a result, the tests can display the vertical failures of piles made of discrete materials and the compressed deformation recorded in the tests is for reference only. That's why this paper only analyzes the failures caused by lateral restraint on piles made of discrete materials.

After careful observation of how the cylindrical mold fails in the loading tests, it is found that all model piles suffer from local buckling failure on the side of the cylindrical mold whether loading is conducted step by step placing weights on self-designed loading device or performed continuously on the loading press. No bulging failure ever occurs on the side of the pile. The results indicate that A4 paper cylinder mold could provide effective lateral restraint, thus limiting the bulging deformation at the pile side. When the cylindrical mold is made of newspapers, the failure mode is local bulging on the cylindrical mold and the failure is located in a certain range below the top of the pile.

Then, make a comparison between the loading modes of Groups D, H, E & I. Group D and Group H have the same pile length (L=100mm) and pile diameter (D=30mm), while Group E and Group I also have the same pile length (L=100mm) and pile diameter (D=40mm). The difference lies in loading modes. For Group D and Group E, weights are added step by step onto the self-designed loading device; For Group H and Group I, a loading press is used to exert loads continuously at the speed of 5mm/min. In the two loading modes, the stress-compressive deformation curves are basically the same, but the ultimate stress differs sharply. The loading press mode generates a much higher ultimate stress than the self-designed loading device. For instance, the ultimate stress of Group D and Group H is 168kPa and 1,349kPa respectively, indicating that the ultimate stress in loading press mode is 8 times higher than that in manual mode. Similarly, the ultimate stress of Group E and Group I is 129kPa and 1,006kPa, which also proves that the ultimate stress in loading press mode is roughly 8 times higher than that in manual mode. See Figure 2. This is mainly because the loading process of the self-made loading device is greatly affected by the manual operation, such as the eccentric action of heap loading. Although the two loading methods have a great influence on the ultimate bearing capacity of the model piles, they have little effect on the failure modes. The failure modes have a strong correlation with the strength of the packing materials of the model piles. Buckling failure would occur if the packing materials are A4 paper, and bulging failure would occur if the packing materials are low-strength newspapers.

Statistics on failure location show that when model piles are 100mm long and 20mm in diameter, the distance between the failure location and the top of the pile is 1.8D (D stands for pile diameter, the same below); when the model piles are 30mm in diameter, the distance between the failure location and the top of the pile is 1.4 D for Group D and Group F, and 1.2D for Group H; when the model piles are 40mm in diameter, the distance between the failure location and the top of the pile is 0.5D, 0.8D and 0.8D for Groups E, G & I respectively. The relatively short distance for Group E may be related to the low compacted density of the filler. As the sectional area of the confinement increases, the failure location gradually moves toward the top of the pile. This is mainly due to the weakening of the restraining effect of the packing material on the filler with the increase of the sectional area of the confinement. In addition, if pile diameter is fixed at 20mm, the distance between the failure location and the top of the pile changes from 1.1D, 1.3D to 1.8D as the pile length is altered from 60mm, 80mm to 100mm. It seems that the distance has something to do with pile length. However, due to the lack of sufficient test data, the assumption is yet to be verified.

All in all, the failure location of all model piles falls within 1.8D from the top of the pile. Therefore, in the design of composite foundation with sand piles, it is necessary to pay attention to the treatment of foundation soil within 3D from the top of sand piles. The vertical bearing capacity of sand piles can be improved by increasing the lateral restraint within 3D from the pile top.

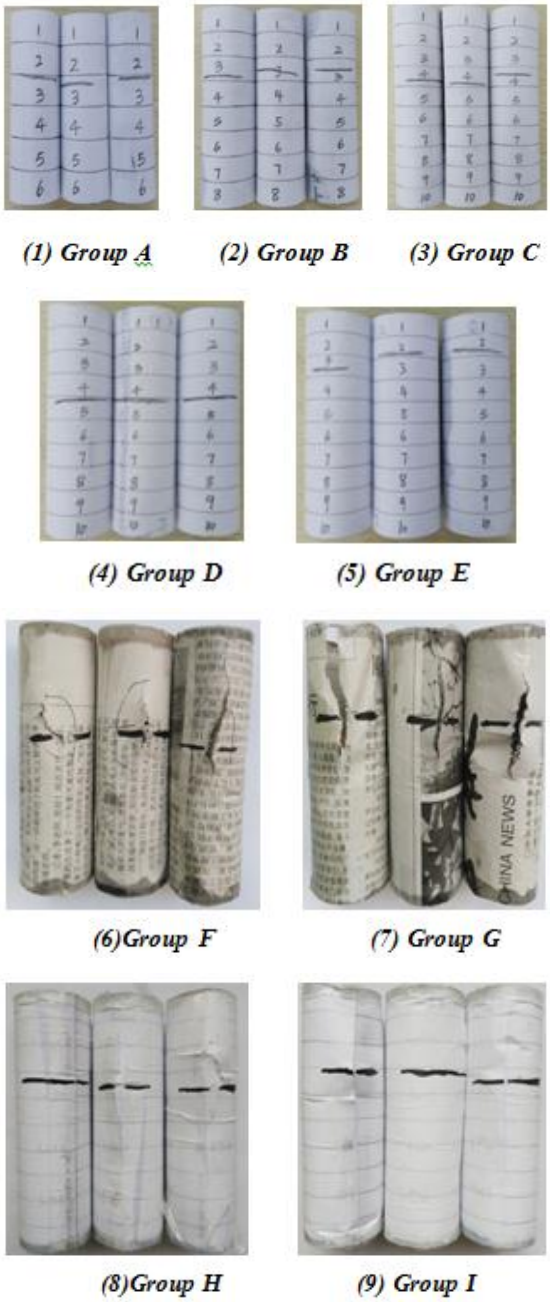


Figure 4: *Failure Locations and Patterns of Model Piles*

5. Conclusions

The following conclusions can be drawn from the aforementioned tests and analysis:

(1) To create model sand piles, the author makes hollow cylindrical molds with A4 paper and newspaper, and fills in the molds with sand. Similar to the way inter-pile soil laterally restrains sand pile in a composite foundation, the cylindrical molds apply lateral restraining force to the filler. The test results and failure modes prove that the cylindrical modes made of A4 paper or newspaper act as a confinement, providing effective lateral restraints to the filler inside, and the failures are largely the same with those on field sand piles. Suffice it to say that the model piles are reasonably designed.

(2) The vertical bearing capacity of model piles is obviously influenced by the strength of the packing material, the packing density of the filler, and the sectional area of the confinement.

(3) Whether the failure mode is buckling or bulging is determined by the strength of the packing material of the model piles. The failure location of the model piles has a high correlation with the sectional area of the confinement and compacted density. Buckling or bulging failure is most likely to hit the area within 1.8D below the top of the pile (D stands for pile diameter).

(4) The tests indicate that the vertical bearing capacity of single pile made of discrete material can be improved significantly by increasing the lateral restraint within a certain distance from the pile top. Therefore, in the design of soft soil foundations, reinforcement within a certain distance from pile top, e.g. the addition of a confinement, helps to improve the vertical bearing capacity of sand piles. This may provide a good idea for the future design of sand piles.

This study only weighs the lateral restraining effect of the soil around the pile, and does not consider the vertical deformation of surrounding soil during the loading process. In future research, we need to improve the test plan and dig deeper into the issue.

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