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On composite foundation with different vertical reinforcing elements under vertical loading: a physical model testing study*

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Abstract: A physical model facility was designed, built, and setup for conducting model tests on a composite foundation in a soil ground. The model tests were carried out on a composite foundation with different combinations of vertical reinforcement elements in the same soil ground. Via the analysis of the collected data the characteristics of the composite foundation with different reinforcing elements were obtained, including the characteristics of load-settlement curves, column stresses, stresses of the inter-column soil, pile-soil stress ratio, and load-sharing ratios of columns and soil. Results from the model tests reveal the mechanism of a composite foundation with different reinforcing elements quantitatively. It is concluded that both a composite foundation with a combination of steel pipe pile and sand column and that with a combination of concrete pile and lime column have a higher bearing capacity than the composite foundation with only sand columns with the same conditions of soil ground and loading. A composite foundation with lime column and sand column embodies no much better performance than that with sand columns only.

Key words: Steel pipe pile, Concrete pile, Lime column, Sand column, Composite foundation, Model test, Pile-soil stress ratio
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1 Introduction

Composite foundation is one type of artificial ground. During the ground treatment, part of the soil is enhanced or replaced, or reinforced materials are set in the natural ground; therefore, the reinforcement area is made up of the soil and the reinforcement. In recent years, composite foundations have been increasingly applied in supporting buildings, highways, and other infrastructure, and meanwhile have achieved significant economic and social benefits. According to the direction of reinforcement elements, Gong (2002) proposed that the composite foundations could be classified into horizontal reinforcement composite foundations and vertical reinforcement composite foundations. Generally, vertical reinforcement elements are called columns or piles. In terms of material and rigidity of vertical reinforcement structures, vertical reinforcement composite foundations may be classified as granular material column composite foundations, flexible column composite foundations and rigid column composite foundations. Given that every type of columns has its advantages, disadvantages and limitations, design methods for multi-element composite foundations were proposed in recent years (Zheng *et al*., 2004). A multi-element composite foundation is formed by including two or three types of the aforementioned piles or columns, and accordingly, the advantages of each column or pile would be mobilized sufficiently. The geosynthetic and vertical reinforcement structural elements were also combined to reinforce the soft soil (Koerner, 2000; Han and Gabr, 2002). The bearing capacity of a multi-element composite foun-

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dation is much larger than that of a foundation without reinforcement or with a single reinforcing element when other conditions are kept the same; in addition, the settlement of a composite foundation is reduced significantly. A growing number of engineering cases have indicated that multi-element composite foundations are more reliable than a composite foundation with a single type of columns. Multi-element composite foundations have been increasingly recognized as promising in foundation engineering (Poorooshasb and Meyerhof, 1997; Zheng *et al*., 2008).

As a new technique for ground treatment, the mechanism of a multi-element composite foundation is still not well-known and the design method is not well established. Among some research conducted in this area, the analytical solutions for composite modulus of a multi-element composite foundation under both elastic and plastic conditions were derived by applying the parametric variational principle of the minimum potential energy based on the bilinear elasto-plastic model for soil and the deformation consistency of pile and soil (Zheng *et al*., 2003). The solutions are useful for calculating the composite modulus of a multi-element composite foundation. Liang *et al*. (2003; 2005) applied an integral equation approach to analyze a composite foundation with hybrid piles. By simulating the cushion using the Winkler springs, the effect of the cushion was taken into consideration, and then the second kind of Fredholm's equations were deduced to solve the problems. By the numerical calculation, compression of the cushion, load shared by piles and subsoil, load transfer characteristics and stress distributions of subsoil were all obtained. The results of a multi-element composite foundation mentioned above were yielded under some assumptions and conditions. Therefore, we need more theoretical and experimental research on the engineering behavior of the multi-element composite foundations and more reasonable analysis methods in order to spread the use of multi-element composite foundations.

Model testing is one important method deployed by researchers and engineers to study the reinforcement mechanism and the reinforcement effect of a composite foundation. For example, Pan *et al*. (2000) conducted laboratory model tests to investigate the behaviour of single piles in soft clay subjected to lateral soil movements and to determine the ultimate soil pressure acting along the pile shaft. From tests on a single passive pile, they obtained that the ultimate soil pressure was $10.6s_u$. Sharma *et al*. (2004) implemented a series of tests to investigate improvement in load-carrying capacity and reduction in bulging of a granular pile in soft clay by geogrid reinforcement. The study revealed an increase in the load-carrying capacity of geogrid-reinforced piles. By applying a physical model experiment on cement-soil mixing columns in soft clay, Yin and Fang (2006) studied the consolidation behavior on soil-cement mixing columns treating soft marine clay in Hong Kong. Wu and Hong (2008; 2009) carried out a series of triaxial compression tests in laboratory to investigate the response of sand columns encapsulated by geotextiles. Their analytical results revealed that the interactive mechanism at the soil-inclusion interface and the mechanical behavior of the inclusion significantly affected the axial stress-strain response of the reinforced column. And the reinforced granular column embedded in clay exhibited a significant increase in axial resistance over columns loaded under constant chamber pressure.

Based on a simple pile model, Liu *et al*. (2003) determined the stresses on the top of different piles and the stresses of the soil between piles by the field plate load tests on a pile composite foundation, and analyzed the variation of the pile-soil stress ratio and the failure pattern for this new type of composite foundation. By comparing with the in-situ test data of the single piles and the soil between piles nearby, they checked the reduction coefficient and the influence factor for the bearing capacity of each type of pile and the soil between piles. Through in-situ tests on multi-element composite foundation, Wang *et al*. (2005) analyzed pile-soil stress ratio, load-sharing ratio and bearing capacity factors of the piles and soil of multi-element composite foundations. Zhu *et al*. (2007) examined in-situ experiment data of subgrade improved by plain concrete pile and mixed-in-place pile under bad geological conditions and the condition of different filling construction materials. It showed that surface layer stress of composite foundation with plain concrete pile improved by plain concrete was focused on pile and was diffused to deep layer; hence there existed the single pile effect. But concerning subgrade improved by the mixed-in-place pile, the stress was focused on the tip and bottom of pile and the load was transferred to soil under the bottom of pile and substratum.

Most tests mentioned above were about the composite foundation formed by a single type of piles or in-situ tests on multi-element composite foundations. However, little research including model tests had been conducted on multi-element composite foundations. Model tests have advantages over field tests, e.g., low cost, easy controlling of the test conditions, and convenient implementation of parametric studies. Therefore, to reveal features of multi-element composite foundations, the authors designed and performed a series of laboratory experiments on multi-element composite foundations with different combinations of reinforcement columns/piles. A number of significant conclusions were drawn based on the analysis of experimental results. The findings herein are very helpful for theoretic research and applications for designing multi-element composite foundations.

2 Apparatus and setup of physical model tests

2.1 Apparatus

The apparatus for physical model tests in this study (Fig. 1) consists of five parts: a model box, an instrumentation system, a loading part, a reaction part, and a lifting part. The loading part includes a hydraulic jack, a manual hydraulic pump, a proving ring and a pressure gauge. The instrumentation system comprises a data logger and transducers, for example, earth pressure cells (EPC), settlement sensors.

As shown in Fig. 2, the model box, including a drainage system and box body, has dimensions of 800 mm×800 mm×1200 mm. The box was made of normal steel plate; rustproof lacquer was painted on the inner and outer walls of the model box. A permeable steel plate and a loading plate were all stainless steel plates with a thickness of 30 mm. The loading plate was 500 mm×500 mm. To reduce the friction between the wall of the model box and the filled soil, a thin layer of lubricating oil was placed before filling on the inner wall of the model box and a layer of plastic membrane was stuck on the oil.

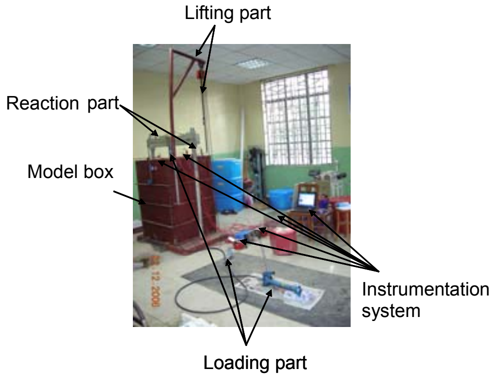

Fig. 1 Physical model testing facility

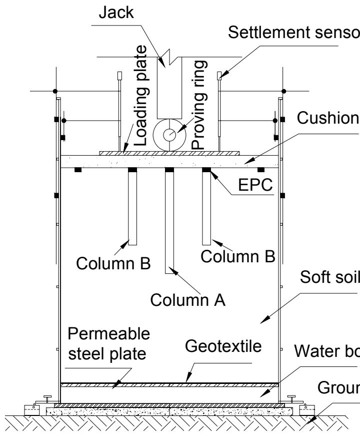

Fig. 2 Sketch of the physical model test facility

2.2 Material

The soft soil in the model test was silty fine sand taken from the Yangtze River near Xudong Village, Wuhan City, China. Properties and parameters of the soil were obtained from lab tests (Table 1). The silty fine sand was used to fill in the model box layer by layer with the same density. The thickness of every filled-soil layer was 50 mm. Each soil layer was compacted to design elevation by a self-made hammer. Before the next soil layer was filled, the soil

Table 1 Properties and parameters of the soil used in the physical model tests

Soil	Unit weight γ (kN/m^3)	Water content w (%)	Specific gravity G_s	Optimum water content w_{op} (%)	Maximum dry density ρ_{dmax} (mg/m^3)	Modulus of compressibility E_s (MPa)	Cohesion c (kPa)	Angle of internal friction ϕ (°)	Coefficient of permeability K (cm/s)
Silty fine sand	19.18	16	2.69	9.76	1.955	23.4	20	28	1.25×10^{-3}

on the surface of the layer was loosened. The cushion material in the model test was coarse sand, with a water content of 3.21%. The thickness of the cushion was 50 mm.

2.3 Layout and installation of columns

The steel pipe pile used in the model test was a seamless steel pipe which was at the length (*L*) of 400 mm. The thickness of the pipe wall was 2 mm. The steel pipe pile was installed by pushing the pile into the soil.

The concrete pile was a precast pile of mixed coarse sand with ordinary Portland cement. The average strength of the cubic specimens under the standard curing condition of 28 d was 10.26 MPa. The length and diameter of the concrete pile was 400 mm and 40 mm, respectively. The concrete pile was pushed into the soil ground.

The lime columns were installed using a polyvinyl chloride (PVC) tube as a mould. After being filled in the tubes, the mixture was compacted layer by layer to form the lime column. Proportioning of the lime columns was that the volume ratio of quicklime to fly-ash was 1:2. The maximum size of the quicklime grains was 5 mm, the average density 1.55 mg/m^3, the length of the lime columns 300 mm, and the design diameter of the lime columns 40 mm.

The sand columns were installed by the tube sinking method. The sand of the sand columns was coarse sand with a water content of 3.21%; its density, coefficient of permeability, and specific gravity were 2.12 mg/m^3, 6.34×10^{-2} cm/s and 2.66, respectively. The length and design diameter of the sand columns were 300 mm and 40 mm, respectively.

The columns' layout is shown in Fig. 3. Details are listed as follows:

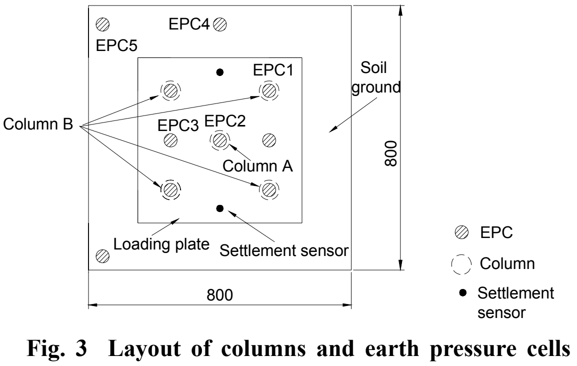

Fig. 3 Layout of columns and earth pressure cells (EPCs) (unit: mm)

(a) In laboratory experiments on a multi-element composite foundation of steel pipe pile and sand column, Column A was a steel pipe pile and Columns B were sand columns.

(b) In laboratory experiments on a multi-element composite foundation of concrete pile and lime column, Column A was a concrete pile and Columns B were lime columns.

(c) In laboratory experiments on a multi-element composite foundation of lime column and sand column, Column A was a lime column and Columns B were sand columns.

Furthermore, layout of the earth pressure cells (EPCs) in the model test of a multi-element composite foundation is shown in Fig. 3. EPCs on the column were embedded at the centre of the column top. The EPCs in the ground soil were embedded at the midpoint between two gravel columns. In addition, there were several micro EPCs outside the loading plate. They were used to measure the effect on the soil beside the wall of the model box when the columns were compressed. All EPCs were installed at the same elevation.

2.4 Experiment procedure

To reflect the reinforcement characteristics of (a) a rigid column and granular material columns, (b) a rigid column and flexible columns, (c) a flexible column and granular material columns in a multi-element composite foundation, we especially designed five cases of model tests on a steel plate under vertical loading:

(a) soil ground without any reinforcement;

(b) a composite foundation with sand columns only;

(c) a composite foundation with a steel pipe pile and sand columns;

(d) a composite foundation with a concrete pile and lime columns;

(e) a composite foundation with a lime column and sand columns.

In these tests, all soil conditions were kept the same. The arrangement of model tests on the sand column composite foundation was almost the same as tests on a composite foundation of a combination of different vertical reinforcing elements. At the same time, the setup and testing procedure of the facility, including loading mode and data acquisition, etc., were all kept the same. Lime columns were all cured for 7 d after being installed, then the load was applied.

3 Results and analysis

Data from the five cases of tests were obtained, as reported in this section. The data are interpreted and presented in terms of curves of pressure-settlement (*p*-*s*), curves of pressure-stress (*p*-*σ*) on each test point of the multi-element composite foundation, curves of pile-soil stress ratio, and curves of load-sharing ratio.

3.1 *p*-*s* curves

Curves of *p*-*s* are shown in Fig. 4 for the five cases mentioned above. The bearing capacity of a composite foundation with certain vertical reinforcing elements is obviously higher than that of the soil ground without any reinforcement (Fig. 4). Under the lower foundation pressure, the relationship of pressure versus settlement is almost linear for a multi-element composite foundation. But with increase of the pressure, the relationships show plastic yielding and the foundation soil was in a plastic deformation state. The multi-element composite foundation of a steel pipe pile and sand columns and that of a concrete pile and lime columns have a higher bearing capacity than that of the composite foundation of sand columns only (Fig. 4). But the bearing capacity of the multi-element composite foundation with lime columns and sand columns is not much different from that of the composite foundation with sand columns only for improving the silty fine sand.

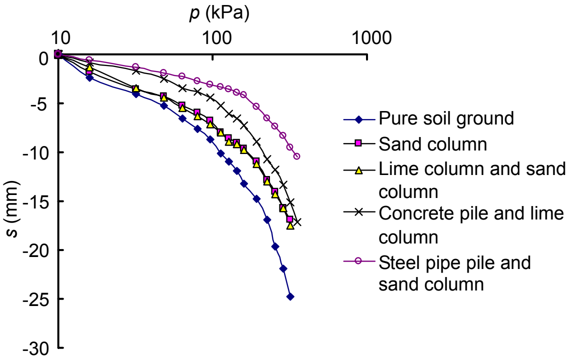

Fig. 4 Curves of *p*-*s*

3.2 *p*-*σ* curves

Figs. 2 and 3 show the locations of all columns labeled as Column A or Column B. Column A is in the center of the foundation. Due to symmetry, all other columns except for the central column shall have the same response as the column labeled as Column B. The average vertical stress on the top of four columns named as Column B is σ_1, the vertical stress on the top of Column A is σ_2, and the average vertical earth pressure on the top of the soil surface below the plate is σ_0. Fig. 5 shows curves of p-σ_1, p-σ_2, and p-σ_0, where *p* is the total average foundation pressure from the three cases of a composite foundation with a combination of different vertical reinforcing elements.

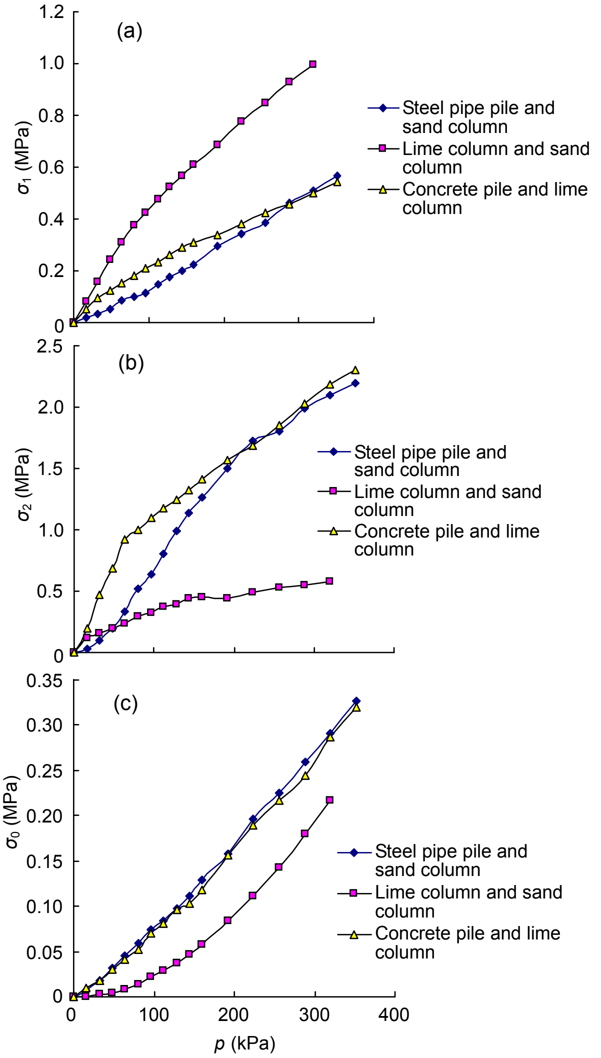

Fig. 5 Curves of *p*-*σ*

(a) Curves of p-σ_1; (b) Curves of p-σ_2; (c) Curves of p-σ_0

From Fig. 5a, the following observations and discussion can be made regarding the measured vertical stress σ_1. With the increase of the foundation pressure, the increase rate of σ_1 in the multi-element composite foundation with one lime column in the centre and four sand columns was the greatest. Because the lime column was the weakest so that the four sand columns took more share of the foundation pressure. In contrast the increase rate of σ_1 with one steel pipe pile and four sand columns was the lowest. This is because the steel pipe pile was the strongest so that the four sand columns took less share of the foundation pressure.

From Fig. 5b, the following observations and discussion can be made regarding the measured vertical stress σ_2.With the increase of the foundation pressure, the increase rate of σ_2 in the multi-element composite foundation of one lime column and four sand columns was the lowest. This is because the lime column was the weakest so that the lime column took less share of the foundation pressure. In contrast the increase rate of σ_2 in the multi-element composite foundation of one concrete pile and four lime columns is the greatest.

From Fig. 5c, we can examine the average vertical stress of the soil underneath the foundation plate. The average soil stress σ_0 in all three cases increases with the foundation pressure. The increase rate of σ_0 in the multi-element composite foundation of one lime column and four sand columns is the lowest.

In addition, the data observed by micro EPCs indicated that the model, as designed reasonably, could reveal the mechanism of multi-element composite foundations quantitatively.

3.3 Curves of pile-soil stress ratio

The relationships of pile-soil stress ratio with the foundation pressure under the vertical loading on multi-element composite foundations are shown in Fig. 6. The parameters n_1 and n_2 are the average vertical stresses of all columns labeled as Columns B and A over the average vertical stresses of the soil below the plate, respectively. The parameter n_0 is the average stress of all columns over the vertical stress of the soil below the plate.

The n_1-value of the composite foundation with one lime column and four sand columns is the highest (Fig. 6a). In addition, the n_1-value of the composite foundation with one lime column and four sand columns decreases quickly with the foundation pressure toward a stable value. The n_1-values of the other two are close to each other. The n_2-value of the composite foundation with one lime column and four sand columns is the largest (Fig. 6b). The n_2-value decreases quickly with pressure and approaches a stable value. The n_2-value of the composite foundation with one concrete pile and four lime columns is slightly larger than that of the composite foundation with one steel pipe pile and four sand columns when the pressure is smaller than 130 kPa. The variation and trend of n_0 are similar to those of n_1 and n_2 (Fig. 6c).

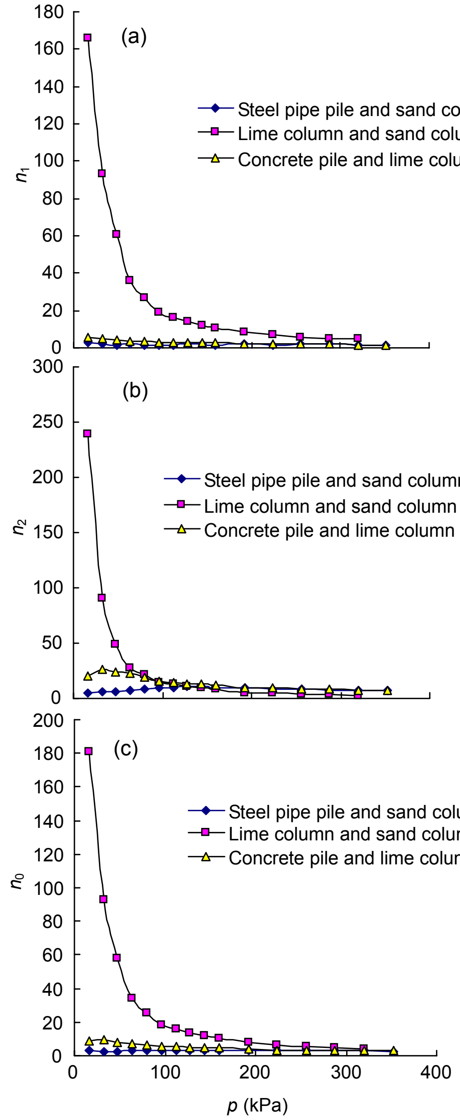

Fig. 6 Curves of *n-p*

(a) Curves of n_1-p; (b) Curves of n_2-p; (c) Curves of n_0-p

3.4 Curves of load-sharing ratio

The load-sharing ratio of Column B is defined as the total load on the top of the four columns labeled as Column B over the load on the foundation plate. The load-sharing ratio of Column A is defined as the load on the top of Column A over the load on the foundation plate. The load-sharing ratio of soil is the total load on soil over the load on the foundation plate.

The load-sharing ratio of Column B of the composite foundation with one lime column and four sand columns is the largest, and that of the composite foundation with one steel pipe pile and four sand columns is the smallest (Fig. 7a). Interestingly, the ratios of both the composite foundation with one concrete pile and four lime columns and the composite foundation with one steel pipe pile and four sand columns come together as the foundation pressure increases.

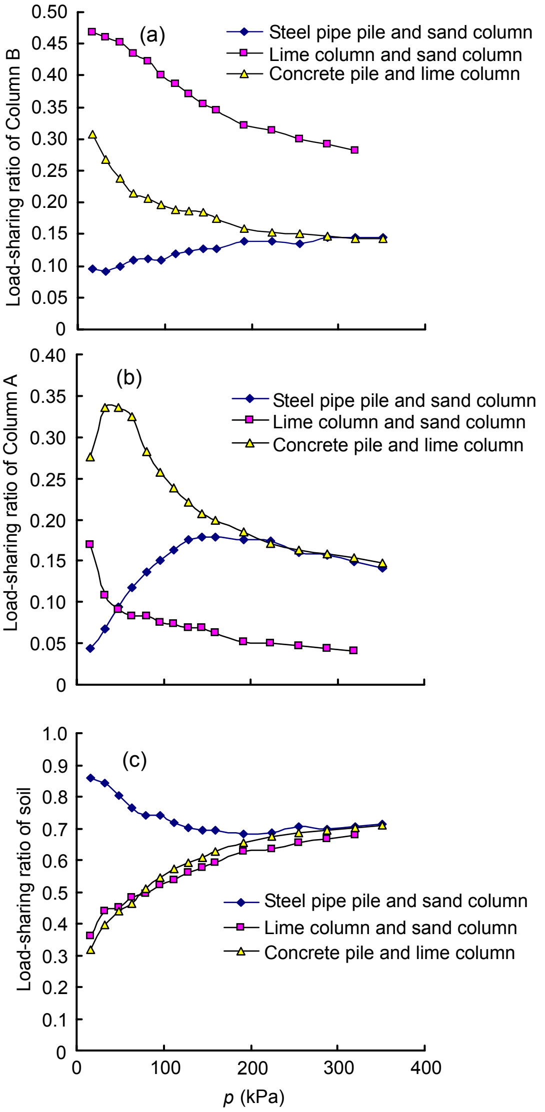

Fig. 7 Curves of load-sharing ratio of (a) Column B; (b) Column A and (c) soil

The load-sharing ratio of Column A of the composite foundation with one concrete pile and four lime columns is the largest (Fig. 7b). The load-sharing ratio of Column A of the composite foundation with one steel pipe pile and four sand columns increase firstly and then decrease slowly. However, the ratio of the composite foundation with one lime column and four sand columns decreases.

Fig. 7c indicates that the load-sharing ratio of soil in the composite foundation with one steel pipe pile and four sand columns is the largest, decreasing initially and then increasing slightly to a stable value. The ratios of the other two increase continuously. Because the steel pipe pile was the strongest.

4 Conclusion

A special physical model test facility has been developed, produced and used to conduct model tests on a composite foundation without or with different vertical reinforcing elements (structures such as columns and piles). After the analysis of the experiment results, the following conclusions may be drawn:

(a) The composite foundation with one steel pipe pile and four sand columns and that with one concrete pile and four lime columns have a higher bearing capacity than other cases. The composite foundation with one lime column and four sand columns has about the same capacity as that with five sand columns.

(b) The relationships of pressure-settlement, stress of the columns, soil stress between columns, pile-soil stress ratio, and load-sharing ratio of columns and soil are obtained from the test data, very helpful for understanding the mechanisms of these composite foundations with different reinforcing elements.

Using the physical model facility, more research on multi-element composite foundations can be done. The performance of these multi-element composite foundations can be investigated by changing one design parameter at a time, for example, the length and diameter of columns/piles, replacement ratio and strength of columns, the thickness and modulus of the cushion, the type and compactness of the soil, etc.

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