Load-settlement behaviour of composite caisson-pile foundation (CCPF) in sand

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Abstract. Caissons and piles are commonly used foundation types for deep water bridges. Caisson is appropriate for long-span bridges, deep alluvial deposits, liquefiable soils, and significant vessel collisions, although they can occasionally become problematic because of difficulties in sinking and insufficient earthquake resilience. Because of its extensive length, decreased rigidity, limited vessel crash protection, and challenging construction requirements, pile foundations are not appropriate for deep sea. A composite caisson-pile foundation (CCPF), also known as a caisson and pile combination, can be used as a solution to the aforementioned issue. It is an innovative hybrid foundation that takes into account the benefits of both foundation kinds. The CCPF reduces construction costs and time while providing creative answers to difficult site conditions in deep water. This foundation structure is commonly used for river and sea crossing bridges. However, due to a lack of significant research on its geotechnical and structural properties, CCPF has not been extensively used. Reduced scale model tests on instrumented CCPF in sand under static vertical loads were carried out based. The load-settlement responses of the foundation under static monotonic vertical loading are presented and discussed in this study.

Keywords: Load settlement; Pile foundation; Caisson foundation; Composite Caisson-Pile Foundation; CCPF

1 Introduction

Caissons and piles are the two most popular deep-water foundation types for bridges spanning rivers and seas. For long-span bridges [1, 2] and in rivers where the depth of alluvial deposits and scour at the base of pier foundations might be rather significant [3, 4], a caisson foundation—also known as a well foundation—is acceptable to meet the criteria for stability and serviceability. Caissons work well in liquefiable soils [5] but are susceptible to strong seismic motion, as shown by recent incidents like the 1995 Kobe Earthquake [6]. However, its construction has been plagued by recurrent obstacles due to difficulties in sinking to the desired depth. For instance, it took more than 10 years to finish the caisson foundations for a five-span, 175 m long bridge in Lumbini, Nepal's strategic road network (Fig. 1) because there were unanticipated hard strata within the foundation's design depth [7]. Numerous bridge projects in Nepal, India, and China had similar issues [2, 8, 9].

Fig.1. Problematic bridge construction due to caisson sinking issues in Tinau River, Nepal

Contrarily, pile foundations are more adaptable and favoured in situations when the ground's hard strata are significantly deeper and have a much lower bearing capacity than caissons. However, due to its limited ability to withstand vessel impact and difficulty in construction as a result of its extensive length and reduced rigidity, it might not be the best option to use in deep water. To address these issues, the caisson and piles may be combined to create the cutting-edge Composite Caisson-Pile Foundation (CCPF), a hybrid foundation that utilizes the best aspects of both types of foundations while minimising their drawbacks. Fig. 2 shows the schematic diagram of CCPF system.

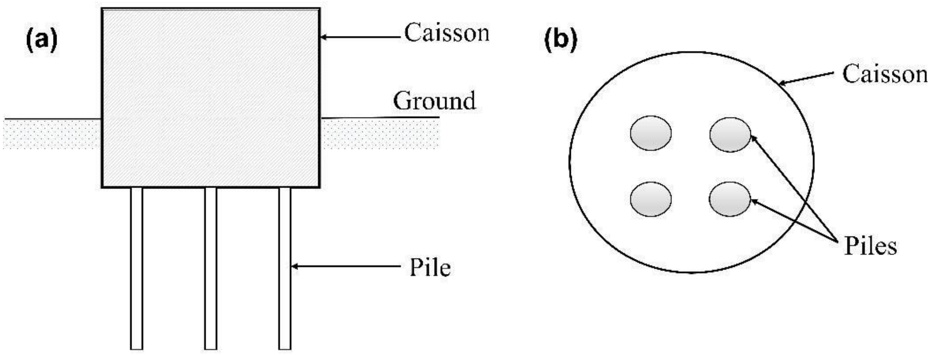

Fig. 2. Composite Caisson-Pile Foundation (CCPF): a schematic diagram

CCPF provides innovative solutions to complex site conditions in deep-water and reduces construction time and cost. Compared to conventional foundations, the CCPF may effectively minimize the length and embedment depth of the caisson and pile foundation, reducing construction complexity and risk. Guo et al. [10] conducted a series of tests on the load-bearing capabilities of composite foundations. Huang et al. [11] and Zhong and Huang [12] studied the performance of CCPF under vibration loading. The seismic response of the composite foundation was evaluated by Zhong and Huang [13] using centrifuge tests. However, the research on CCPF is still scanty. Moreover, load-settlement behaviour of CCPF is still unknown. Due to which, the application of CCPF has been minimal. More research and development initiatives are desperately needed to give designers more confidence in adopting such innovative foundation systems.

2 Material and Methods

Material Characterization

Sand

Uniformly graded Ganga sand from Ganga river was used as the soil bed for the model tests at the laboratory setup of the Indian Institute of Technology Kanpur (IITK), Kanpur, India. The physical and mechanical properties of Ganga sand were obtained. The soil type based on USCS classification was SP (poorly graded sand) with sand fraction of 98.19 %. Specific gravity and unit weight of the sand was obtained as 2.67 and 14.07 kN/m^3 respectively. Angle of internal friction (ϕ) was 32.5˚, whereas maximum and minimum void ratio were obtained as 0.99 and 0.70, respectively.

Caisson and Pile Model

To conduct experimental loading tests, the design dimensions of Tinau River Bridge (Lumbini Province, Nepal), designed by the Department of Roads, Nepal, were taken as a prototype. An appropriate similitude philosophy relevant for 1-g load tests given by Iai [14] was used, and a scaling factor of 50 was predicted for a prototype M30 grade RCC caisson and piles. The models were prepared using mild steel with the modulus of elasticity and Poisson's ratio as 210 GPa and 0.3, respectively. The properties of the prototype and model of caisson and piles are shown in Table 1.

Table 1. Properties of prototype and model of caisson and pile

Properties	Prototype	Model
Material	Concrete	Mild Steel
Modulus of elasticity, E (N/mm^2)	27,386	2,10,000
Poisson’s ratio, υ	0.2	0.3
External diameter of caisson (mm)	7000	90
Thickness of caisson (mm)	900	18
Caisson depth (mm)	9000	180
Pile diameter (mm)	800	10
Pile depth (mm)	23000	460
Number of piles	4	4

Test Setup and Loading Arrangement

For the model experiments, a 0.6 m sided cubical tank was utilized. To reduce the boundary impact, the side boundaries of the tank are maintained at a distance of more than 2.5 times the diameter of the caisson, and the bottom boundary is maintained at a distance greater than 10 times the diameter of the pile from the pile's top.

The loading tests of CCPF was conducted at structural laboratory of the Indian Institute of Technology (IIT), Kanpur, India. The setup and arrangement of CCPF with piles upto bottom ($CCPF_{bottom}$) and CCPF with piles upto top of caisson ($CCPF_{top}$) are as shown in Fig. 3. In both cases, a 10 kN capacity hydraulic jack was utilized to apply a vertical load on the model foundation. The loading frame consists of four 1.5 m tall vertical columns, two on each side, and two horizontal beams. A 500 kN capacity calibrated load cell was fitted to the jack to measure the load.

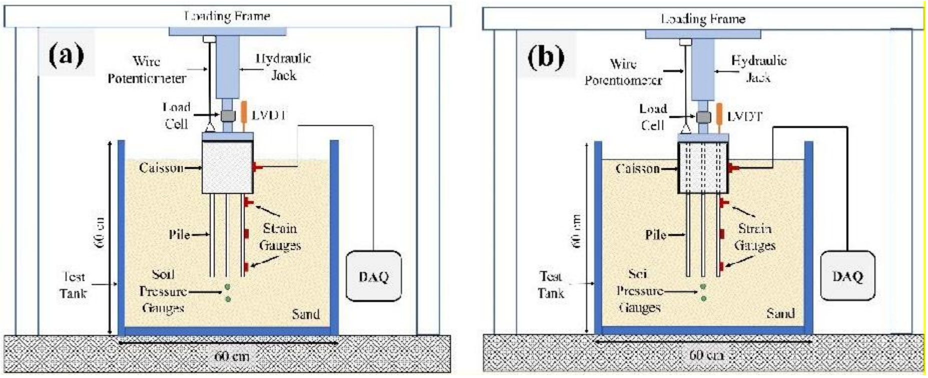

Fig. 3. Schematic diagram showing the experimental setup for Vertical Load Testing of (a) CCPF with piles upto bottom (b) CCPF with piles upto top of caisson

In the model setup, the sand bed was prepared to have relative density of 40 % (loose) and 70 % (dense). The calibration test demonstrated that a 15 cm fall height is optimal for reaching the specified relative density. Likewise, the hammer blow method achieved a relative density of 70 %. The total height of the tank (60 cm) was split into equal intervals from the inner side by creating signs every 10 cm in height to facilitate the placement of a specific weight of sand in a defined volume to achieve the desired density through compaction. Fig. 4 shows the procedure of preparing the sand bed and installing the test model in the tank.

A total of 12 sensors were used to measure various responses of the foundation and soil as shown in Fig. 3. All sensors were linked to a system for data acquisition (DAQ) system. LabView 2017 software was used to program the system to automate the data collection.

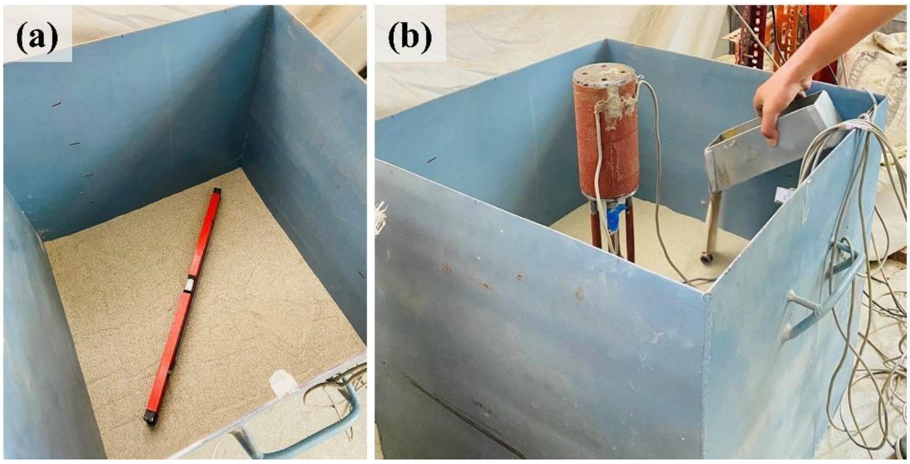

Fig. 4. Sand bed preparation for CCPF model tests

Test Procedure and Schemes

After the installation of model, the load was applied to model through loading plate placed on the caisson. All other sensor instrumentation was conducted, as shown earlier. According to the standard test method suggested by ASTM-D1143 (2013), the failure load can be defined for the settlement exceeding 15 % of the caisson diameter for vertical loading. Hence, the vertical loading continued until the settlement reached at least 14 mm. In this way, 6 vertical loading tests were conducted, the details of which are provided in Table 2.

Table 2. Testing schemes for CCPF

ID	Test name	Soil condition	Pile length (cm)
1	Caisson	Loose	-
2	Caisson	Dense	-
3	CCPF	Loose	28
4	CCPF	Dense	28
5	$CCPF_{top}$	Loose	46
6	$CCPF_{top}$	Dense	46

3 Results and Discussions

Load-settlement response

The test findings are reported in terms of load–settlement behavior and load improvement ratio. The load versus settlement plots of single caisson, CCPF with piles up to caisson top ($CCPF_{top}$) and CCPF with piles up to caisson bottom ($CCPF_{bottom}$) in two relative densities (loose and dense) are shown in Fig. 5.

The ultimate load-carrying capacities of single caisson, $CCPF_{bottom}$, and $CCPF_{top}$ measured at 10 mm settlement, i.e., corresponding to 10% of the caisson diameter were found 188, 267, and 334 N, respectively for loose sand. It can be seen that the $CCPF_{top}$ and caisson alone exhibit the highest (334 N) and lowest (188 N) load carrying capacities, respectively. Likewise, in dense sand condition, ultimate load-carrying capacities of single caisson, $CCPF_{bottom}$, and $CCPF_{top}$ at 10 mm settlement were observed 904, 1186 and 1213 N, respectively. It is clear that the load-carrying capacity of CCPF increases as the density of the soil bed increases for all studied cases (Fig. 5). The addition of piles is found to be beneficial in improving the load capacity of the caisson as shown in Fig. 5.

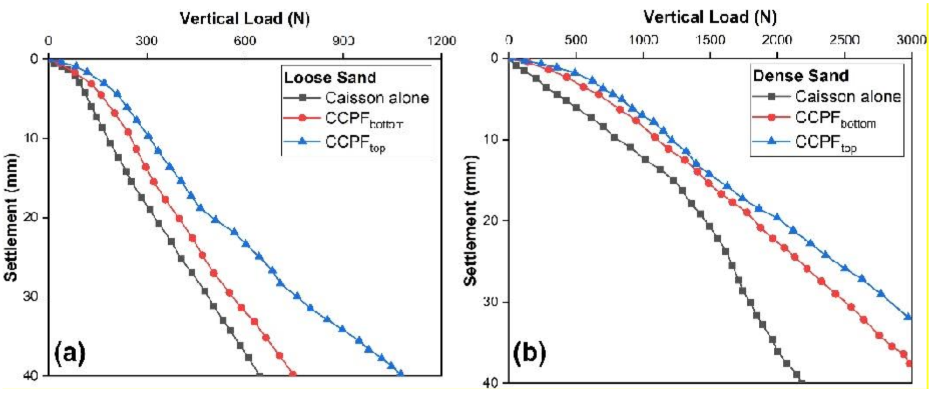

Fig. 5. Load vs displacement curve for (a) loose (40 %) and (b) dense (70 %) sand

As shown in Fig. 5, the load-settlement response of a CCPF system subjected to vertical loading seems to occur in three stages. In the first stage, load-induced settlement increases almost linearly. In the second stage, the load-settlement response becomes more curved, as load-induced settlement increases more than in the first stage. This phase might be referred to as the crucial phase of the foundation. In the third stage, load-settlement behavior returns to being almost linear, although the settlement grows rapidly despite the load not increasing significantly. The results are in close agreement with the results of Wang et al. [14] conducted for CCPF.

Load improvement ratio

The enrichment of the external load-carrying capability of the caisson at a particular settlement is defined as the load-improvement ratio (LIR). It is a non-dimensional parameter expressed as a fraction of the load conveyed by the CCPF to the caisson alone at a given settlement as given by Equation 1.

$$\text{LIR} = \frac{P_{ccpf}}{P_c} \qquad (1)$$

where, P_{ccpf} and P_c are load carried by CCPF and caisson alone at respective settlements, respectively.

In this study, the improvement in the load capacity of the caisson, at 5, 10, 15, 20, 25 and 30 mm settlements, due to the presence of settlement reducing piles is estimated and presented in Fig. 6. It shows the load improvement in different CCPF models in loose and dense sand conditions. It can be seen that, in both sand densities, CCPF with piles upto top of caisson ($CCPF_{top}$) shows higher 'LIR' values than $CCPF_{bottom}$. From the figure, it can be noted that, the 'LIR' varies in almost nonlinear fashion with settlement.

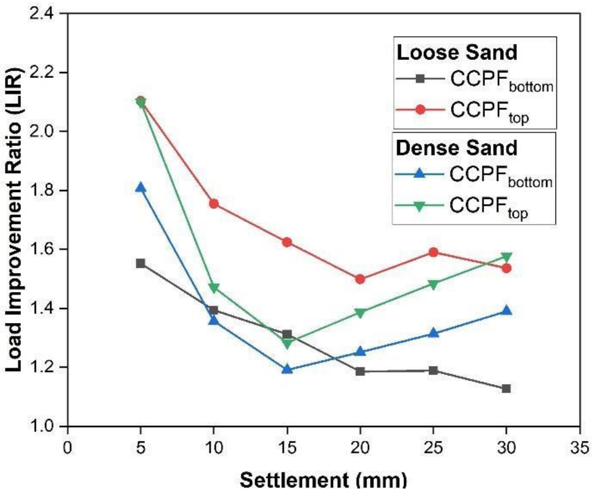

Fig. 6. Load improvement ratio for loose (40 %) and dense (70 %) sand

4 Conclusions

Following are the conclusions of the experimental study on CCPF:

- The composite foundation (CCPF) maximizes the vertical load carrying capacity of the soil while successfully controlling the settlement. Generally, the caisson could support the top weight and be utilized as a platform for bridge construction. After bridges are erected, the piles beneath the caisson may be used to regulate the settlement.
- The vertical load-carrying capacity of CCPF increases as the density of the soil bed increases.
- The improvement of vertical load capacity is found to be increasing with increased length of pile.
- Load-settlement response of a CCPF system subjected to vertical loading occurs in three stages: at first increases linearly, then becomes more curved and finally returns to being almost linear.
- Load improvement ratio (LIR) varies in almost nonlinear fashion with settlement in both vertical as well as lateral loading conditions. $CCPF_{top}$ shows higher LIR values than $CCPF_{bottom}$. In addition, with increase in length of piles, the LIR values have been found increased.

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