Proceedings of 11th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: March Volume: 11

A Review on the Behavior of Composite Well-Pile Foundation (CWPF) under Static and Dynamic Loading

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Abstract

Despite the numerous benefits, practitioners are hesitant to adopt well foundations due to sinking issues caused by complicated geology. To address this peculiar scenario by utilizing well foundations, a composite well-pile foundation (CWPF) has been developed recently as an innovative type of deep foundation. Additionally, this technique may also be utilized to retrofit existing well foundations. CWPF can be loaded in a variety of ways, including vertical loads imposed by the superstructure, lateral loads caused by water current, ground pressure and seismic loads, and moments induced by eccentric loading. Numerous research has been undertaken on the behavior of composite foundations when these loading are applied independently or in combination. The purpose of this article is to summarize these state-of-the-art efforts to provide an overview of the behavior of composite well-pile foundations.

Keywords

Composite well-pile foundation, CWPF, performance, static loading, dynamic loading, review

1. Introduction

Heavy foundation mass is required to satisfy the stability and serviceability requirement in the case of a long-span bridge or in bridges where the lateral load is enormous [1, 2]. Moreover, in the Indian subcontinent, there are numerous rivers where the depth of alluvial deposits can be quite high [3] and the scour around the base of the pier foundations can be very deep, particularly when the piers are placed in an active channel of water [4]. A well foundation is a very appropriate type of foundation for such conditions. As it has a high section modulus, it can withstand enormous horizontal and vertical stresses even when the unsupported length is long on the scouring river bed [2, 5]. Originated in India, well foundations have been used since the Mughal period as a deep foundation in important buildings, bridges, and other structures, especially in South Asian countries like India and Nepal. But, due to improper geotechnical investigation, complex geology, and lack of expertise in the design and construction of wells, there have been frequent problems causing delays in construction time and overrunning the project's cost [6]. One of the major issues is undesirable sinking or difficulty in sinking the wells to design depth.

Construction of many bridges is being delayed and costly in Nepal due to unexpected hard strata within the design depth of well foundation [7]. As a result of difficulties in well sinking, several contractors left the job, and some contractors took more than ten years to complete the well foundations. For example, a 5-span 35m c/c length bridge (Figure 1) located in a strategic road network in Lumbini, Nepal, took more than ten years to complete its well foundations. Initially, well foundation of 7m diameter and 17m depth was designed but during construction, the contractor could not sink the wells (right abutment and two other piers as shown in Figure 1) below 7m with available technology and capacity as a thick conglomerate layer was encountered. Similar problems have been observed in many bridge projects such as the Sunkoshi Bridge (Khurkot), Kaligandaki Bridge (Ridi), Sunkoshi Bridge (Ghurmi), which were designed by the Department of Road (DOR), Nepal. In India also, like in Nepal, several bridge constructions projects such as Brahmaputra Bridge (Tezpur), Ganga Bridge (Bhagalpur), Pasighat Bridge (Arunachal), Tapi Bridge (Maharashtra) have been delayed or halted because of similar issues with the

Figure 1: Tinau river bridge obstructed due to well sinking issues (Source: Bridge Branch, DoR, GoN)

well foundation. Moreover, in many cases, existing well foundation might have to be strengthened or reinforced with piles or micropiles to enhance its bearing capacity [8]. For which case, the standard guidelines are not well developed.

Despite several advantages, practitioners are being reluctant to use well foundations due to sinking difficulties because of complex geology. To overcome such a peculiar situation by taking advantage of well foundation, a composite well (also called as caisson)-pile foundation (CWPF) is recently proposed as an innovative type of deep foundation. The schematic layout of this composite foundation is as shown in Figure 2. CWPF system can greatly reduce the height of the well by connecting the lower pile groups to the upper well, and improves its mechanical behavior under lateral load. Qiongzhou Straits bridges in China have adopted this foundation type as an early initiation. This concept can also be used to retrofit the existing well foundation. With the benefit of the piles, the height or the embedded depth of the well can be effectively reduced, significantly reducing the construction difficulty.

However, in contrast to the extensive research on the common forms of bridge foundation, such as pile and well foundations, limited research has been carried out on CWPF [9]. The aim of this article is to summarize some of the pioneer and innovative literature works conducted on CWPF systems. This article categorizes these findings based on the type of loading applied on the composite foundation constructed by well and piles.

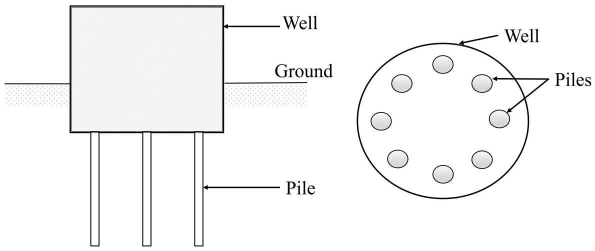

Figure 2: A sample layout of composite well-pile foundation (CWPF) system

2. Performance of CWPF under Static Loading Conditions

2.1 Foundations Subjected to Vertical Loads

Wang et al. [10] conducted four groups of tests on sandy soil to determine the vertical bearing behavior of composite foundation. Piles and well were replicated in these models using thin-walled steel tubes and steel plate, respectively. The experimental setup used in the study is as shown in Figure 3. The study clearly demonstrated that a single well could bear the load successfully but with excessive settlement; the piles beneath the well were able to greatly control the settlement, and the control effect enhanced with pile length. Existing piles might withstand soil pressure and increase the vertical bearing capacity of a single well, resulting in a composite foundation with a greater vertical bearing capacity than a single well. At first, the well carried about 80% of the vertical load, but as the load increased, piles were added to bear approximately 40% of the load. Thus, the composite foundation could maximize the bearing capacity of the soil while successfully controlling settlement.

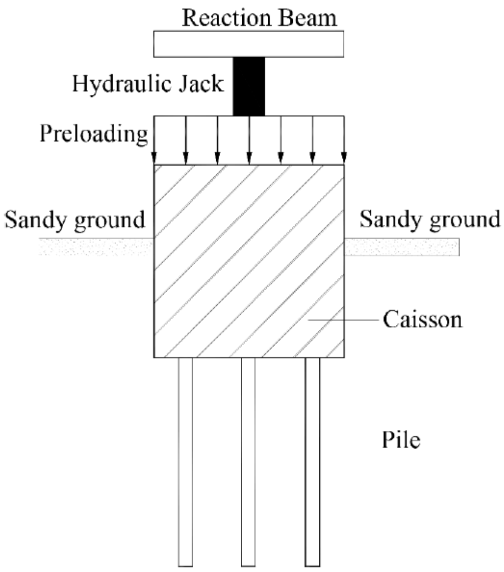

Figure 3: Experimental setup for vertical loading test [10]

2.2 Foundations Subjected to Horizontal Loads

Wang et al. [11] studied the horizontal bearing behavior of composite foundations in the laboratory using four different bridge foundation models based on the Qiongzhou Strait bridge project in China. Simultaneously, the load sharing ratio between the well and the piles is studied. The layout of loading setup is given in Figure 4. The findings of the study indicated that adding skirts, steel pipe piles, or both steel pipe pile and skirt increases the horizontal ultimate bearing capabilities of a single well foundation by 1.2, 1.6, and 2 times, respectively. The bending moment of the pile body is rather significant and is maximum at its centre. Moreover, the horizontal load is carried mostly by the top well foundation and the soil layers immediately above the middle upper section of pile.

Along with this study, horizontal behavior of composite foundation was assessed by Guo et al.[12]. The results highlighted that after the application of horizontal load, the top of the pile can be considered as embedded end due to the rigid well. The moments, displacements, and soil resistance of piles subjected to horizontal loads were found to be less than those of a single pile without restraint. The well's restraint on the piles can significantly improve the pile's horizontal bearing capacity. With an increase in the number of piles, the horizontal load bearing capacity increased proportionately.

Figure 4: Overall layout of horizontal load test [11]

2.3 Foundations Subjected to Combined Horizontal and Vertical Loads

The behavior of composite foundation due to the combination of vertical and horizontal loads was experimentally evaluated by Guo et al. [12] conducting model experiments on single pile and a series of CWPFs in silty clay (Figure 5). Through the study, the efficiency coefficients of well-pile composite foundations were determined for a variety of pile numbers, constraint conditions on the pile top, and well loads. It was concluded that friction beneath the well bottom and vertical force on the pile top contribute to the composite foundation's bearing capacity being improved further.

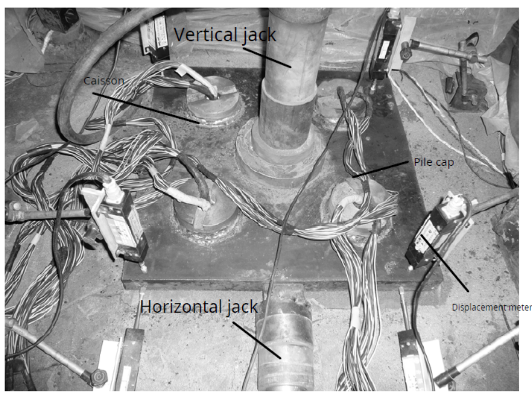

Figure 5: Schematic diagram of combined horizontal and vertical loading setup [12]

3. Performance of CWPF Under Dynamic Loading Conditions

As a foundation for deep water, the CWPF will undoubtedly be confronted with many lateral dynamic stresses caused by water flows, waves, wind, and probable vehicle brakes or boat collisions. Consequently, a credible analytical approach is required to determine the lateral dynamic response of CWPF, which may serve as a theoretical base for the foundation's popularization and implementation. At moment, few academic studies on the CWPF have been conducted, particularly on the dynamic response. Luckily, pertinent research findings on the well and pile group may be employed to examine the dynamic properties of CWPF.

Among the early stages of these studies, Huang et al. [13] highlighted that the piles under the well can improve the dynamic performance of the foundation significantly. In this point of view, Zhong and Huang [14] proposed a simplified method for the lateral response of composite foundation based on the dynamic Winkler model. As per this study, a Winkler model for the lateral vibration of the CWPF was established by combining the well and the pile group, where the well was modelled using the four-spring Winkler model and the pile group was modelled using axial-lateral coupled vibration equations. Figure 6 shows Winkler model for lateral vibration of the CWPF, wherein, d represents the embedment depth of the well, D is the length of the well part, and Q_0 and M_0 are the dynamic horizontal force and moment applied on the top of the CWPF, respectively. The study employed embedded footing impedance to determine the coefficients of the four-spring Winkler model for wells, with an adjustment to the rotational embedment factor to account for the geometrical difference between shallow footings and wells. Ultimately, based on the analysis of a CWPF example, it was established that installing piles is an effective technique to strengthen the foundation's capability of resisting lateral dynamic loads. However, because the lateral reaction of the CWPF could not be reduced permanently by increasing the pile length, it was advised from an economic standpoint to have some control over the pile length.

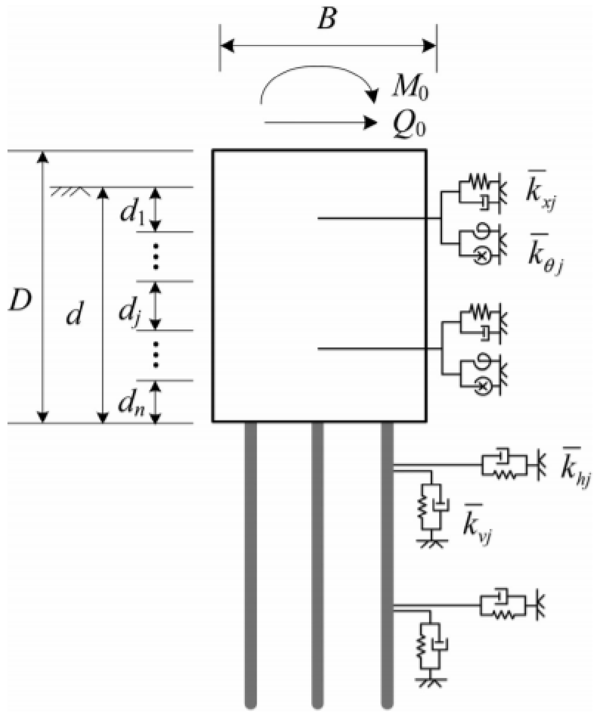

Figure 6: A sample numerical model of the composite foundation based on the BNWF [14]

Given that the CWPF is a composite of a well and a pile group, its impedance matrix K_{wp} may be constructed by multiplying the well and pile group impedance matrices together, namely

$$K_{wp} = K_w + K_p \tag{1}$$

where K_w and K_p are the impedance matrixes of the well and the pile group respectively.

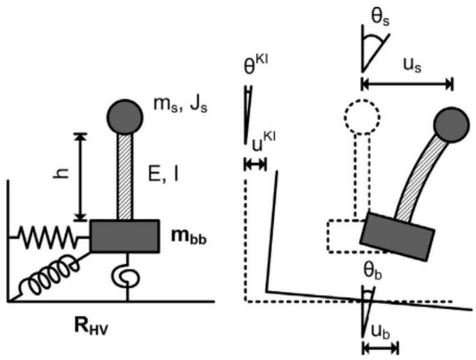

Figure 7: Simplified model for the interaction of CWPFs with structures, as well as the lateral deformation of this model [15]

As a companion study, Zhong and Huang [15] examined the seismic response of the CWPF and the dynamic interaction between it and the superstructure under conditions in which the external loadings are caused by earthquake waves in the soils, rather than lateral loadings as in the previous paper [14]. Both articles were concerned with the effect that the piles built beneath the well may have on the entire system. The study indicated that because the frequency features of an earthquake are difficult to anticipate, there is a possibility of damage to the well due to a pseudo-resonance. According to the study in this paper, installing piles can be an efficient means of mitigating this calamity if the main frequency of the earthquake is near to the well's pseudo-resonance. This was also highlighted by Zhong and Huang [14] saying that composite foundation is an efficient model to increase the seismic resistant capability of the soil-foundation-superstructure system than individual foundation types. Zhong and Huang [15] simplified the foundation–structure interaction by replacing the foundation with a mass matrix and lateral impedance (Figure 7).

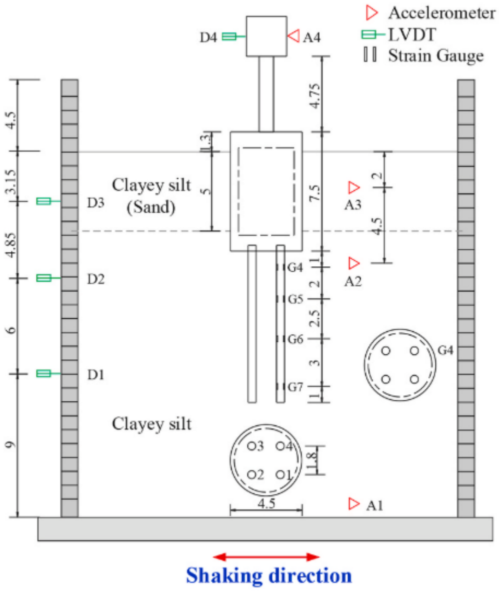

Figure 8: Schematic front view of the CWPF model with 2×2 piles and the instruments in the centrifuge tests carried out by Zhang et al. [16] (prototype scale, dimensions in m)

Zhang et al. [16] conducted a series of centrifuge shaking table tests on CWPF to investigate its seismic response (Figure 8). The CWPF model was used, with 2×2 and 3×3 piles embedded in homogeneous clayey silt or layered soil consisting of dry sand overlaid by clayey silt, respectively. The superstructure was simplified as a lumped mass and connecting column. These centrifuge test findings suggested that both soil condition and pile arrangement influenced the CWPF's seismic reaction, and future research combining experimental and numerical modelling should be done to study additional parameters impacting the CWPF's seismic behavior. Although increasing the number of piles beneath the well can mitigate part of the superstructure acceleration, the CWPF model with the design of 3×3 piles was more sensitive to earthquake-induced displacement in this investigation than the model with the configuration of 2×2 piles.

To assess the effects of scouring on the responses of the CWPF due to long-term lateral cyclic load, Zhang et al. [17] carried out a series of model experiments at 1g using two different scour depths and two different cyclic load amplitudes. The results indicated that one-way cyclic loading enhanced the stiffness and capacity of the composite foundation's post-cycle behavior when subjected to monotonic stress. Furthermore, the scouring had a detrimental influence on the composite foundation's behavior, resulting in a lower capacity. Additionally, the composite foundation performed well under long-term cyclic load due to the low accumulation rate of residual rotation at the composite foundation's head. Additionally, an exponential equation was proposed based on the model test results to estimate the cumulative residual rotations with high cyclic numbers as follows:

$$\theta = \theta_1 N^{\alpha} \tag{2}$$

where θ_1 is the residual rotation for the first cyclic load, which is calculated from the point of interaction with vertical axis when N = 1 and the exponent α is a constant as laboratory tests of a cyclically loaded monopile. It was noted that α = 0.31 and 0.39 respectively for the cyclically loaded suction caisson as given by LeBlanc et al. [18] and Zhu et al. [19]. On this regard, Zhang et al. [20] demonstrated that the cumulative residual displacements or rotations are dependent on the cyclic load characteristic and scour depth, with the most onerous loading condition occurring between one-way and symmetric two-way loading. Additionally, the effect of scouring may be sensibly analyzed by substituting the post-scour static capacity for the static capacity before scouring.

Dynamic centrifuge tests were performed to investigate the seismic response of CWPF [16, 21], however, in a reasonably complicated deep-water environment, it is highly usual for the bridge foundation to become acquainted with waves and severe winds instead of earthquakes. As a result, greater attention must be paid to its behavior on horizontal dynamic stresses. Zhong and Huang [22] created a dynamic Winkler soil model for the lateral response of CWPF in the frequency domain, although it was limited to elastic studies. In light of soil's nonlinear behavior, indeed, it is important to outspread the study beyond linear elastic behavior. Additionally, tests must be conducted to gain a clear understanding of CWPF's dynamic response to horizontal excitations and to corroborate the expanded nonlinear dynamic Winkler model. Taking this as concern, Tu et al. [23] conducted model experiments on three distinct kinds of foundations, including wells, wells with four piles, and wells with eight piles, to determine their lateral nonlinear dynamic properties under a variety of excitation forces (Figure 9). The test findings demonstrated that the excitation force and scour depth had a noticeable nonlinear effect on the vibration amplitude and resonance frequency of the foundations. In comparison to the well, putting piles beneath the well reduced the vibration amplitude and increased the resonance frequency, and pile structure also had an effect.

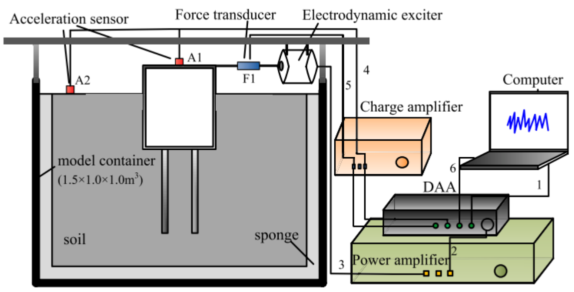

Figure 9: The excitation test schematic diagram performed by Tu et al. [23]

4. Conclusion

The behavior of composite well-pile foundation (CWPF) under different loading conditions were studied through experimental testing, analytical methodology and numerical modelling by different researchers. Owing to the fact that the CWPF is composed of a well and grouped piles, its analysis is pretty complicated due to the large disparity between the well and the grouped piles. Due to the well's shape, it is appropriate to treat it as a rigid body. However, piles are fundamentally different, not just in terms of their slenderness, but also in terms of their interaction with one another.

Keeping this in mind, researchers have conducted studies on static and dynamic performance evaluation of CWPF. Studies highlighted that the composite foundation maximize the bearing capacity of the soil while successfully controlling settlement. Generally, the well could support the top weight and be utilized as a platform for bridge building. After bridges are erected, the piles beneath the well may be used to regulate the settlement. Additionally, it was identified that installing piles would significantly improve the foundation's ability to withstand lateral dynamic loads as well as decrease the risk of damage to the well owing to pseudo resonance during seismic reaction. The composite caisson-piles foundation with various pile configurations in homogeneous or layered soil exhibited markedly different seismic responses, demonstrating the need for additional experimental and numerical studies on additional factors influencing the seismic response of the novel CWPF foundation type. Thus, this review study will be valuable for future advancements in this subject since it will provide an overview of the behavior of CWPF under various loads and settings.

5. Acknowledgement

We are thankful to Er. Jibendra Mishra (SDE, DoR,GoN) for providing data and information related to bridge foundation issues in Nepal. First author acknowledges the help and continuous support from Dr. Santosh Kumar Yadav (Coordinator, MSc Geotech program) and Er. Mandip Subedi (General Secretary, NGS) during the MSc Thesis research. The great help from Er. Abhash Acharya in Latex formatting is highly acknowledged. We also appreciate the help of Bin Jia (Hunan University of Technology, China) to get access of the papers written in Chinese language.

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