Journal of Innovations in Engineering Education
JIEE 2024, Vol. 7, Issue 1.

https://doi.org/10.3126/jiee.v7i1.69391

THAPATHALI CAMPUS
Institute of Engineering
Tribhuvan University

Soil-structure interaction analysis of well foundation

Ishwor Chandra Marahatta[a,*], Sanjay Kumar Jha [b] and Bikash Devkota [c]

[a]*Government of Nepal*
[b]*Geo-Explorers, Inc., PA, USA*
[c]*UniSA STEM, University of South Australia, Mawson Lakes campus, SA, 5095, Australia*

ARTICLE INFO

Article history:

Received 13 September 2024
Revised in 27 October 2024
Accepted 10 November 2024

Keywords:

Well foundation
Numerical analyses
Soil-structure interaction
Displacement

Abstract

Well (caisson) foundation has been used in bridges for a long time to withstand the heavy lateral forces and moments. A better understanding of soil-caisson interaction can help to build a safe and economic well foundation. The behavior of caisson under various soil-structure interaction scenarios was investigated in this study. Different aspects of the well foundation, like load-displacement relationship and variations in axial load capacity with varying parameters of soil and caisson, were studied through numerical analyses.The results showed that the load-carrying capacity of the caisson increased with the improvement of soil properties such as Young's modulus of elasticity (E_s), cohesion (C), friction angle (ϕ), and Poisson's ratio (v), whereas cohesion and friction angle greatly influenced the well capacity. Likewise, load-carrying capacity increased with an increase in grip length and diameter of the well. However, caisson's capacity increased in higher magnitude while increasing its diameter for a constant grip length than increasing grip length for a fixed diameter.

1. Introduction

Nepal has five geological formations ranging from Terai to Tethys Himalaya with Chure, Lesser, and Higher Himalaya in between [1]. As a landlocked and mountainous country, Nepal has the greatest variation in altitude from south to north over 200 km distance from Terai (60 m above sea level) to High Himalayas (> 8000 m above sea level) respectively [2]. Due to this steep geology, Nepal is vulnerable to land degradation-related problems such as landslides and soil erosion including floods [3]. The degraded soils are deposited in the lowland area in the Terai region.

Many bridges constructed in the Terai region of Nepal require a deep foundation. However, several problems were encountered during the construction of the deep foundation which led to the time and cost overrun of the project. This might be due to either the design deficiency in considering appropriate soil parameters and location or the lack of proper project management.

Foundations are the part of the structure that interacts with the soil underneath and transfers the load imposed on the structure along with the self-weight of the structure. They are meant not to fail under the designed load, to safeguard the structure under the application of the design load. If the surrounding soil is weak in bearing capacity, the shallow foundation may not be sufficient, and a deep foundation may be the option. Pile and well foundations are commonly used as deep foundations. Well foundations, also known as open caissons, can be built either on dry beds or sand islands [4]. While considering the scouring depth or bearing capacity of soil, if the foundation needs to be higher than 5-7 m deep, due to heavy temporary shoring requirement for retaining sides, greater earthwork, and potential scouring of loose soil refilled around the foundation, an open excavation leads to be a costlier and hence another option is recommended as well foundation [5].

Well foundations are mostly used as the foundation for bridge abutments and huge waterfront structures exposed to large vertical and horizontal forces [6]. Besides, foundations of heavy structures such as electric towers, chimneys, and others can be well foundations. Such foundations are advantageous for various scenarios such as an obstruction to penetrate piles or positioning

*Corresponding author:
isumb007@gmail.com (I.C. Marahatta)

of drilled piers, to avoid scoring depth, and/or to withstand the heavy lateral forces [6]. In addition, it provides protection against the damaging affinity of floating objects being a massive structure.

In Nepal well foundations have been constructed mostly for the sediment/sand-laden river and till now, such foundations have been designed using the Indian Roads Congress (IRC-45) [7]. It recommends the formula based on the observed behavior of the well foundations and the work done by many researchers in this field. However, the consideration of various soil parameters on soil-caisson interaction needs to be accounted for to capture the largely varying soil of the Terai region of Nepal for better geotechnical design in the local area. This research is focused on the interaction of caisson with soil to observe the capacity of caisson on varying the soil properties, and diameter and grip length of the caisson. The findings of this research can help to better un-derstand the effect of the variability of soil on the construction of a safe and economic well foundation.

2. Research methodology

A finite element method (FEM) was used for the computer modeling. For this, ABAQUS/CAE Version 6.10 [8] software was used. Validation of the model was done from the study of Taiebat and Carter [9]. In their study the soil was assumed to follow the Tresca Failure criterion.As Taiebat and Carter [9] model was run using the different coding technique AFENA, the model parameters including material properties were changed in different trials to achieve the curve as proposed in their model.

Once the model ran under the set of models and material properties produced comparable results for the axial and lateral load, the model was then used to analyze (i) the effect of varying soil parameters such as modulus of elasticity, friction angle, cohesion, and Poisson's ratio of soil, and (ii) the effect of varying grip length and diameter of the caisson on caisson axial capacity. The major components followed in ABAQUS for this study were as below:

2.1. Model geometry

The model created was a three-dimensional cylindrical model as shown in Figure 1. Here D and L represent the diameter and length of the caisson, and 8D and 7D represent the width and depth of the soil column respectively. The two-dimensional model could also be created by se-lecting the modeling space as 2D planar. A required cut and extrude section was performed to represent the proper shape of the model.

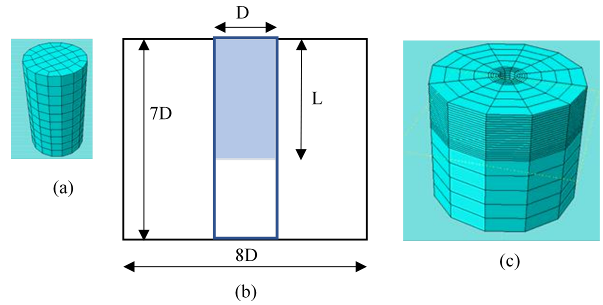

Figure 1: Geometry of a model (non-scaled dimensions are presented) (a) caisson, (b) dimension of caisson and soil column, and (c) soil column

2.2. Material definition and section property

The material and section properties of each part of a model need to be defined in a de-formable body. Here different types of soil properties were assigned to represent different types of soil including properties of concrete. Soil was defined per Mohr Coulomb failure criteria while concrete was defined as elastic material. Sections were defined as homogeneous 3D solids with respective material properties for caisson and soil. Such defined sectional properties are assigned to the respective parts using section assignment under the property module.

2.3. Boundary condition

The boundary conditions along the side of the soil cylinder were set such that it allowed movement only in the vertical direction while at the base of the soil cylinder, the boundary con-dition was assigned such that it did not allow movement in any of the three directions. Further, displacement as per the required value in the direction of gravity was introduced at the central top node in the caisson, as a boundary condition. Loads and boundary conditions were step-dependent, which means that the step/steps in which they became active were specified accordingly.

2.4. Meshing

Differential meshing technique was used in the model as shown in Figure 2, where the soil part was meshed in such a way that all portions with immediate contact with caisson were meshed finer than the portions away from it.

3. Model validation

The caisson's axial and lateral load capacity inside homogenous soil mass under an undrained situation estimated by Taiebat and Carter [9] was used for validation purposes. The geometry is shown in Figure 1. Soil and caisson parameters for their study are presented in Table 1.

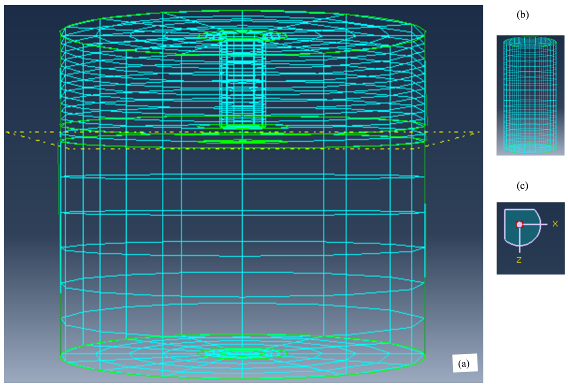

Figure 2: Model showing (a) soil column including soil shaft interface, (b) caisson, and (c) two dimensional axes

Table 1: Geometrical and material parameters of a model

Dry-wet Sequence	Caisson	Soil
Diameter (D)	D	8D
Length (L)	2D	7D
Young's Modulus of Elasticity (E)	$E_c = 1000E_u$	$E_u = 300S_u$
Poisson's Ratio (ν)	-	0.5
Elastic Shear Modulus (G)	-	$\frac{E_u}{2(1+\nu)}$
Here, S_u = undrained shear strength, E_c = undrained Young's modulus of a caisson, E_u = undrained Young's modulus of a soil		

The modeling approach explained in Zienkiewicz and Taylor [10] was used by Taiebat and Carter [9] for small strain creation where the semi-analytical FEM approach was combined with the AFENA program used in the study of Carter and Balaam [11]. Displacement-defined situa-tions were taken for the analyses where vertical and lateral displacements were applied at the ground sur-face and at different depths to the caisson respectively. Besides, two/three displace-ment elements were com-bined to explore the behavior of the foundation under combined action. Undrained conditions were assumed to be maintained through the application of loads at a suf-ficiently higher rate.

The axial load capacity (A_u) under undrained conditions was estimated through the modifi-cation of the conven-tional method suggested by Vesic [12] as in Equation 1 for the caisson of dimension L/D = 2 [9].

$$A_u = 8.9AS_u \quad (1)$$

where A = caisson's plan area.The uplift capacity (U_u) can be calculated through the suggested equations by Deng and Carter [13] with some recommended values for various factors as in Equation 2 for the caisson of dimension L/D = 2 [9].

$$U_u = 19.44AS_u \quad (2)$$

The mechanism of bearing capacity and uplift capacity of soil can be taken as similar but reverse direction [14] and hence Equation 2 can be applicable to estimate the uplift as well as bearing capacity in the compression of the caisson [9]. Furthermore, the reversal of loading did not have significant changes in the outcomes of FEM regarding the axial capacity [9].

For a homogeneous soil, the estimation of the lateral capacity (H_u) under undrained situations can be done using Equation 3 [9].

$$H_u = N_h LDS_u \quad (3)$$

where N_h = lateral capacity factor. It can be expressed as the function of point of load application [13]. Various suggestions for N_h are shown in Table 2.

The outcomes of Taiebat and Carter [9] and this study were compared as shown in Figures 3 and 4. These comparative figures depicted that the model developed in this study is capable of predicting the caisson-soil interaction. This validated model was then used in this study for further analyses.

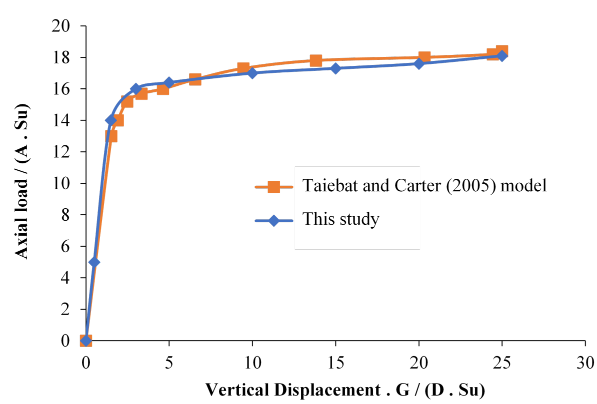

Figure 3: Comparison of model outputs of caisson be-havior under axial load

4. Results and discussion

The effect of various soil parameters including the grip length of the caisson was investigated in the caisson

Table 2: Load Application Points and N_h Values from Various Studies

Deng and Carter [13]		**Aubeny, Han, and Murff [15]**		**Taiebat and Carter [9]**	
Load application point	N_h Value	Load application point	N_h Value	Load application point	N_h Value
Ground level	4.8	Ground level	4.5	Ground level	4
Depth at 0.6L	11.66	Depth at 0.6L	11.1	Depth at 0.6L	10.7
Caisson's tip	7	Caisson's tip	5.5	Caisson's tip	5.3

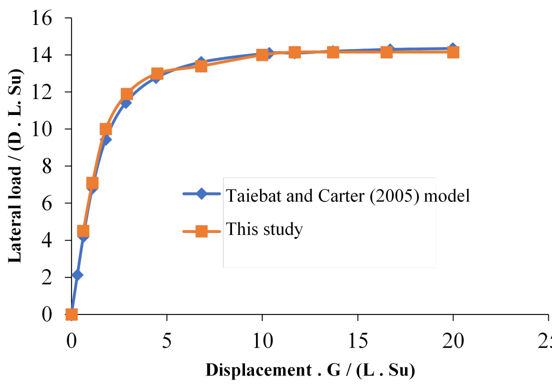

Figure 4: Comparison of model outputs of caisson behavior under lateral load

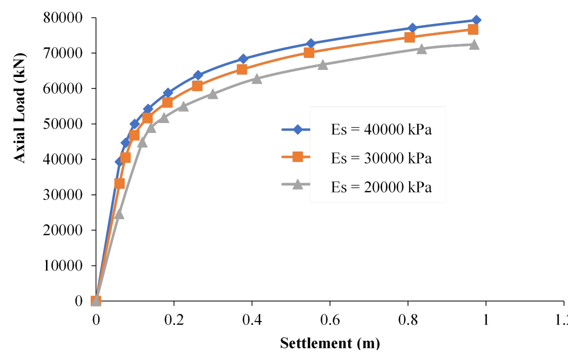

Figure 5: Variation of axial load capacity with Modulus of Elasticity of soil

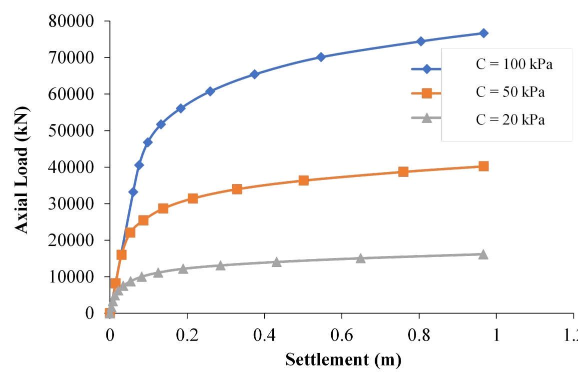

Figure 6: Variation of axial load capacity with cohesion of soil

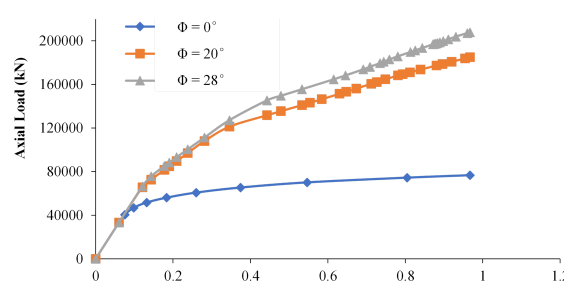

Figure 7: Variation of axial load capacity with internal friction of soil

model as validated above. When the 6 m diameter of the caisson was chosen, as per Table 1, the length of the caisson, soil's depth and diameter would be 12 m, 42 m, and 48 m respectively. The assumed value of Su of soil was 100 kPa, and hence respective undrained Young's modulus of elasticity and Poisson's ratio of soil were taken as 30,000 kPa and 0.5 (from Table 1). Young's modulus of elasticity for the caisson of concrete material was taken as 30 GPa. The model surface interactions were defined as follows:

- Side and base tangential interactions with a friction coefficient of 0.3, for con-crete-soil interaction.
- Side and base normal interactions as hard contact without allowing separation.

The effect of Young's modulus of elasticity (E_s), cohesion (C), friction angle (ϕ), and Poisson's ratio (v) of soil were explored through the caisson model, and the results from the analysis are shown in Figures 5, 6, 7, and 8. It is clear to see that the axial capacity of the caisson increases with the improvement of these soil properties. It is important to note that the cohesion and the friction angle were the most influencing factors for the caisson behavior. Also, the de-crease in Poisson's ratio increases axial capacity as shown in Figure 8.

The effect of variation in diameter and grip length of a caisson was investigated. Figures 9, 10, 11, and 12 show the model outcomes. The comparison of variation

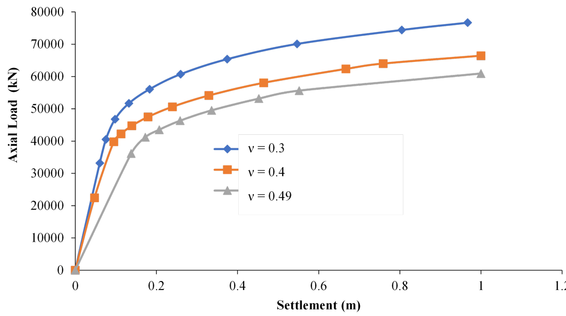

Figure 8: Variation of axial load capacity with Poisson's ratio of soil

in axial load capacity on changing either grip length or diameter of caisson keeping one parameter constant at a time is shown in Figures 13 and 14. It is clear to see that the increment of the caisson's capacity was higher for the scenario of increasing the diameter for a particular grip length than the condition of increasing the grip length for a certain diameter.

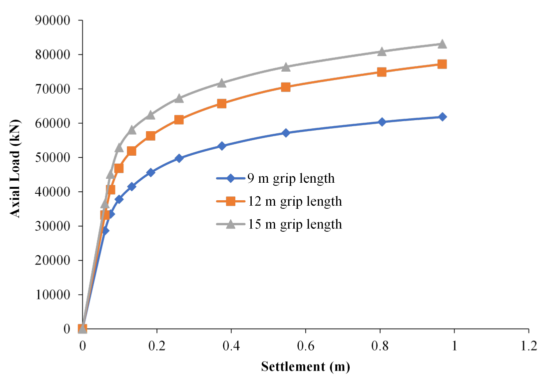

Figure 9: The axial load capacity of a caisson (6m diameter) with varying grip length

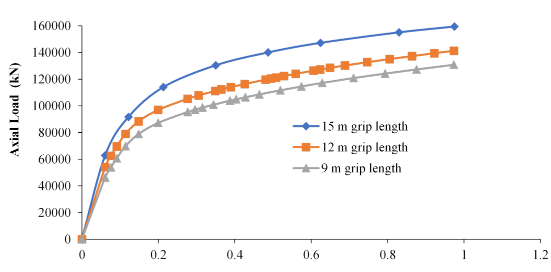

Figure 10: The axial load capacity of a caisson (12m diameter) with varying grip length

The load-carrying capacity of the well foundation was significantly increased with the im-provement of soil properties (increase in modulus of elasticity, additional friction angle for co-hesive soil). Hence, various meth-

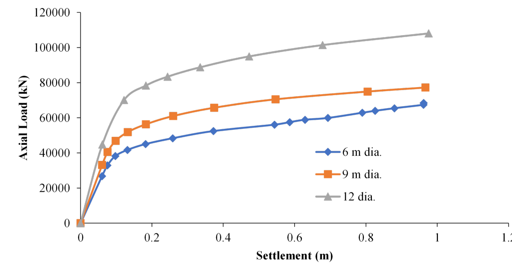

Figure 11: The axial load capacity of a caisson (12m grip length) with varying diameters

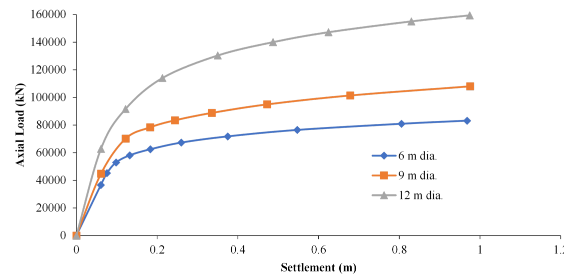

Figure 12: The axial load capacity of a caisson (15 m grip length) with varying diameter

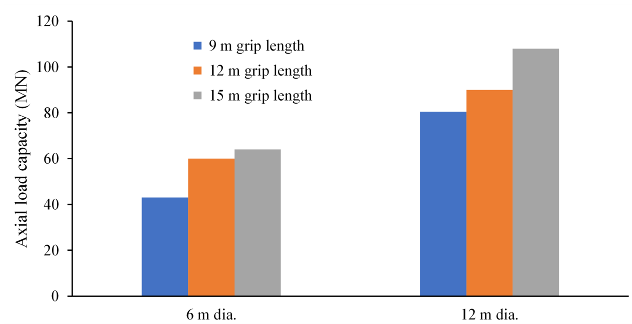

Figure 13: Comparison of axial load capacity of a caisson for a fixed diameter but varying grip length

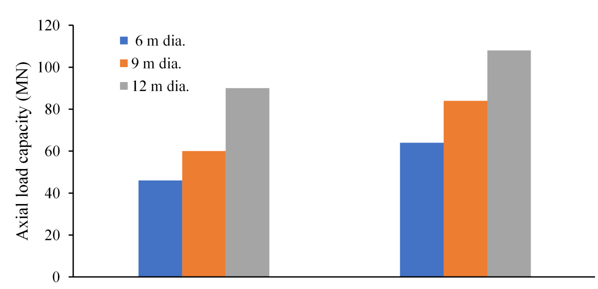

Figure 14: Comparison of axial load capacity of a caisson for a fixed grip length but varying diameter

ods of ground improvement can be applied to improve the soil properties. Conventional methods such as chemical grouting, sand columns, compactions, and so on have been used for this purpose.

5. Conclusions

The behavior of the well foundation under various soil-structure interaction conditions was investigated through the finite element method under axial loading. The following conclusions can be made based on this study:

- The axial capacity of well foundation increases with the improvement of soil properties such as Young's modulus of elasticity (E_s), cohesion (C), and friction angle (ϕ). The cohesion and the friction angle are the most influencing factors for the caisson's behavior.
- Load carrying capacity of caisson increases with an increase in grip length and diameter of the well. Caisson's capacity increases in higher magnitude when increasing its diameter for a constant grip length than increasing grip length for a constant diameter.

References

[1] Department of Mines and Geology. General Geology[EB/OL]. 2024. https://dmgnepal.gov.np/en/pages/general-geology-4128.

[2] Vuillez C, et al. Land use changes, landslides and roads in the phewa watershed, western nepal from 1979 to 2016[J]. Applied Geography, 2018, 94: 30-40.

[3] Chalise D, Kumar L, Kristiansen P. Land degradation by soil erosion in nepal: a review[J]. Soil Systems, 2019, 3(1): 12.

[4] Arora K. Soil mechanics and foundation engineering (geotechnical engineering): In si units[M]. 7th ed. Delhi, India: Standard Publishers Distributors, 2008.

[5] Civil Engineering Home. Well Foundation: Meaning, Advantages, Types, Components & Diagram[EB/OL]. 2022. https://cementconcrete.org/structural/foundation-design/well-foundation/3320/.

[6] Poudel R, Neupane R. A text book of foundation engineering[M]. Kathmandu, Nepal, 2010.

[7] The Indian Roads Congress. Recommendations for estimating the resistance of soil below the maximum scour level in the design of well foundations of bridges[M]. New Delhi, India: The Indian Roads Congress (IRC), 1996.

[8] Abaqus analysis user's manual[M]. ABAQUS, 2010.

[9] Taiebat H, Carter J. Interaction of forces on caissons in undrained soils[C]// ISOPE International Ocean and Polar Engineering Conference. ISOPE, 2005.

[10] Zienkiewicz O, Taylor R. The finite element method[M]. 4th ed. New York: McGraw-Hill, 1989.

[11] Carter J, Balaam N. Afena users' manual[M]. Centre for Geotechnical Research, Department of Civil Engineering, University of Sydney, Australia, 1995.

[12] Vesic A. Bearing capacity of shallow foundations[M]// Foundation Engineering Handbook. New York: Van Nostrand Reinhold, 1975: 121-147.

[13] Deng W, Carter J. Analysis of suctions caissons in uniform soils subjected to inclined uplift loading[R]. Department of Civil Engineering, The University of Sydney, Australia, 1999.

[14] Anderson K, et al. Field test of anchors in clay, ii: Prediction and interpretation[J]. Journal of Geotechnical Engineering, ASCE, 1993, 119: 1532-1549.

[15] Aubeny C, Han S, Murff J. Inclined load capacity of suction caissons[J]. International Journal for Numerical and Analytical Methods in Geomechanics, 2003, 27(14): 1235-1254.