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Research Article

Numerical Study on Load Bearing Capacity of Root-Caisson Foundation

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Innovation has been made in the caisson foundation to support a very large structure resting over a soft soil stratum known as the root-caisson foundation. This technique was executed in China-Yangtze River Bridge. The root caisson foundation was first implemented in the Yangtze River bridge and discovered that the root improves soil structure interaction and increases vertical bearing capacity by 100%. In the present research, a numerical study of root-caisson foundation under combined vertical and horizontal loading was performed using ABAQUS software. Analysis was performed by varying the parameters of root caisson such as the inclination of roots (30°, 45°, 60°, and 90°) spacing(S) between the root floors with respect to diameter (D) of the caisson as (0.5°D, 0.6°D, and 0.75°D) with different loading conditions and results were compared with normal traditional caisson with the same length (L) to diameter (D) ratio. From the test results, the load-settlement behavior of caisson is nonlinear for individual vertical, and lateral load tests and also the same for the combined loading conditions. It is found that the root-caisson has a higher load bearing capacity as compared to that of the traditional caisson. Moreover, in combined loading, the load bearing capacity increases considerably, compared with the ultimate vertical and lateral load capacity.

1. Introduction

The rapid development of infrastructure and the poor soil conditions of the site requires newer technology and method to satisfy the economy, time, and the environment. The root caisson foundation involves the normal traditional caisson with a projection of roots on the caisson walls which resembles the roots of a tree shown in Figure 1.

The building of a root caisson involves sinking a caisson with holes in the side walls and then pushing prefabricated roots into the Earth through the caisson's holes. Concrete will be used to bind the caisson to the roots on the inner face of the caisson. These roots will increase the soil structure interaction and improve the performance of the caisson. It also saves construction costs and time. A study was conducted by Lei et al., on the vertical bearing capacity of root caissons and was found that the axial bearing capacity increases significantly with a reduction in the settlement [2]. Dhatrak et al. performed research on root-caisson found in sand revealed that Root-Caisson foundations are more capable of bearing vertical loads than conventional caissons. Also, Root-Caisson capacities increase as root length, root number, and floor count increases [3]. Huang et al. carried out an analytical study of anchor foundation on nonhomogeneous soils and proposed the method for analysis of root caisson in layered soil. Here a comparative study on the

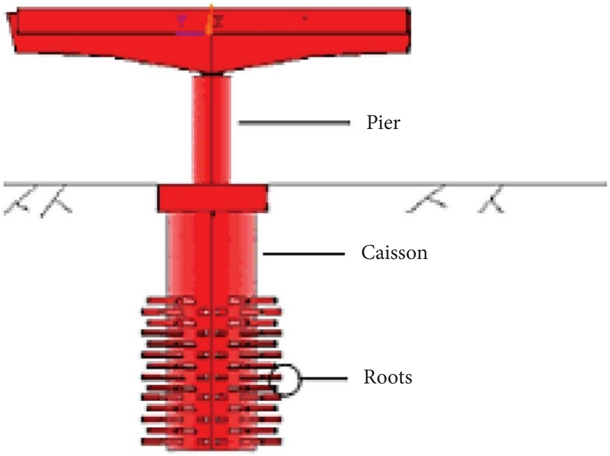


Figure 1: Sketch of root-caisson foundation [1].

actual size of caisson and root-caisson with numerical models have been studied. This work has validated the effectiveness of root caisson in load bearing capacities both in vertical and lateral direction. Caissons that are loaded vertically possess a twice as large a load capacity as simple caissons. When the caisson is lateral loaded, the load-displacement curve does not abruptly change, whereas the root caisson has a much higher lateral stiffness than a simple caisson [4]. Yang et al. performed the test on the rooted bored pile with varying diameters. The results showed piles behave as a friction pile and the root carries the vertical load along with the pile shaft [5]. Zhou et al. executed an experimental study on the bearing capacity of rooted piles under uplift, lateral, and combined loading conditions and confirmed that the bearing capacity of the rooted pile was much greater than the conventional straight pile. Also, an increase in the embedded depth of roots will improve the performance of the pile [6]. Darga Kumar and Narasimha Rao carried out an experimental study on the mobilization of Earth pressures on caissons embedded in marine clay under lateral loads. He performed the test on caisson by varying the ratio of embedment depth, eccentricity ratio of loads, and undrained strength of the soil. Results indicate that the behaviour of the caisson under lateral loading conditions matches well with the field caisson [7]. Deshpande carried out the laboratory investigation and found that the increase of floors, number of roots, and lengths of roots increases the vertical load capacity of the caisson [8]. Alampalli and Peddibotla performed a detailed study on the deflection behaviour of open-ended caisson on sandy soil and shows that the load shared by the skin friction is greater than the base resistance for the higher embedment depth [9]. Zhu et al. measured the bearing capacity of rooted caisson under vertical compressive loading by using the simplified self-–balance method and found that the ultimate bearing capacity of the caisson had been risen by 126% [1]. Fattah et al. carried out numerous research on a different type of footing resting on sandy soil. The parameters considered for this research such as properties of sand as unit weight and angle of internal friction is found to be correct while corelating with this research [10–12]. Mahmood et al. believed that the skirted footing increases the bearing capacity with a decrease in the settlement and improves the load-settlement behavior of the footing. Also, the bearing capacity of skirted footing is dependent on the surface and geometrical properties of the skirt, and characteristics of gypseous soil. This concept has been found to be applicable in this present study [13].

Numerous research studies on root caisson foundations have been done. Out of all, the roots are provided only at the angle of 90° inclination. In this study, the roots are provided in different root inclinations as 90°, 60°, 45°, and 30° and the performance in load bearing capacities of caissons are found out using ABAQUS software.

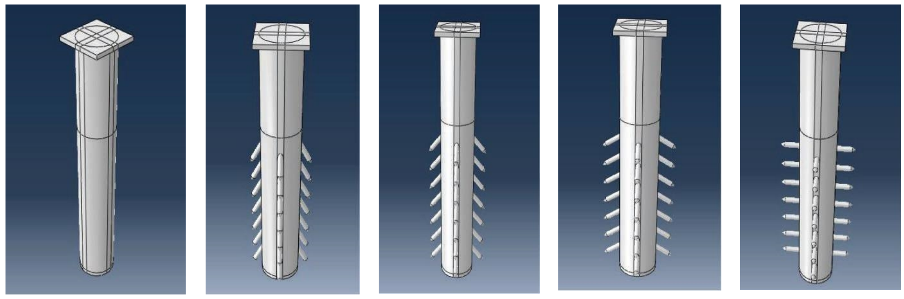
Gong et al., carried out research studies on root caisson foundation subjected to vertical, lateral, and uplift loading conditions with minimum numerical analyses. Therefore, the present study deals with the numerical modelling of root caisson under combined axial and lateral loading using ABAQUS 6.14-1 software. The load-deflection characteristics under axial and lateral loading were studied for the traditional caisson and caissons with root inclinations as 90°, 60°, 45°, and 30°. Combined loading has been done in a combination of axial load measurement with a constant magnitude (20%, 40%, 60%, 80%, and 100%) of ultimate lateral load. For the optimum root caisson inclination, load-deflection behaviour has been studied by varying the spacing between the root floors as 0.5, 0.6, and 0.75 times the diameter (D) of the caisson.

2. Numerical Stimulation

2.1. Modelling of Root—Caisson. Over the past few years, caisson foundations have been increasingly used as alternative foundations for offshore structures. In general, a caisson foundation for an offshore wind turbine often experiences lateral, vertical, and overturning loads simultaneously. In this paper, an open-ended model is developed to estimate the bearing capacity of traditional caisson foundation with root caisson foundation in a sand test bed with the drained condition. Based on the scaling factor law given by Wood the caisson model has been developed [14]. For the present study, a hollow aluminium pipe of an outer diameter of 100 mm and an inner diameter of 80 mm is used as a model caisson.

$$\frac{(EI)_p}{(EI)_m} = n^{4.5}, \tag{1}$$

where "n" is a scale factor, the flexural rigidity of prototype caisson, and flexural rigidity of model caisson, respectively. Lei et al. carried out a field study on root caisson with 6 m diameter and length 39 m which has been taken as a prototype and obtained a scaling factor of 34.15 [2]. An open-ended circular caisson having a diameter (D) as 100 mm and length (L) as 400 mm. The embedment length (L) to diameter (D) ratios (L/D) of model caissons was taken as 4. To execute the static vertical stress on the pile, an aluminium caisson cap of size $120 \times 120 \times 10$ mm is installed at the caisson head.



Traditional caisson | Caisson with 30° roots | Caisson with 45° roots | Caisson with 60° roots | Caisson with 90° roots

Figure 2: Shows the 3D view of modeled traditional caisson and different angles of rooted-caisson using ABAQUS.

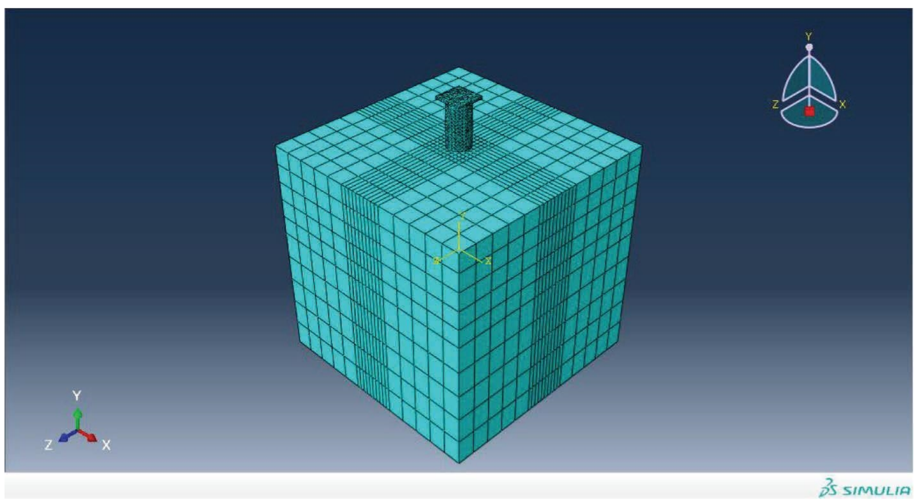


Figure 3: 3D-View of soil model with mesh.

In this analysis, the roots were assumed with the same material properties as such of the caisson, and its dimension was taken as 12 mm diameter (d) and 40 mm in length (l). The L/D ratio of caisson is considered as 4, therefore over the embedded length of the caisson, the roots were fixed at an interval of 50 mm with 4 roots at each floor right angles to each other.

Three-dimensional finite element simulations have been conducted in this study for the evaluation of the load-carrying capacity of root-caisson. Modelling of the root-caisson with different inclinations are 90°, 60°, 45°, and 30° and the traditional caisson was carried out by using ABAQUS. Figure 2. shows the different models of root-caisson. In root-caisson, the spacing of roots considered was 0.5 times the diameter (D) of the caisson. Therefore, there will be a twenty-eight number of roots which are provided in seven layers with 4 roots at each layer.

2.2. Modeling of Soil Model. Caisson was embedded in a rectangular soil model of size 1000 mm × 1000 mm × 800 mm in *X*, *Y*, and *Z* direction to ensure that the boundary effect on the failure mechanisms is small, shown in Figure 3. Numerical modelling of the caisson is done by assuming as Mohr-Coulomb plasticity model. Geometric and nonlinearity of the material were taken into consideration for this study.

2.3. Material Properties. The material used in the caisson foundation and soil model are shown in Tables 1 and 2. The properties of soil have been studied in the laboratory experiments such as sieve analysis, relative density test and direct shear tests for the medium dense sand and incorporated. Generally, the Poisson's ratio for sand ranges between 0.18–0.32, and young's modulus value is obtained from stress-strain analysis on the sand.

2.4. Load and Boundary Conditions. The following boundary conditions are adopted for this soil model:

(i) Horizontal restraint is provided on the outer faces of the soil model (left & right of the soil model).

(ii) Vertical restraint is provided on the bottom face of the soil model.

(iii) Finer meshes with very small element sizes were used to depict the soil-structure interaction. For analysis, 10-noded linear brick element were used to model the 3D soil elements.

Table 1: Soil properties are considered in this study.

Properties of soil	Values
Material model	Mohr–coulomb
Young's modulus MPa	25 MPa
Poisson's ratio, μ	0.35
Unit weight, γ, kN/m^3	17 kN/m^3
Friction angle°	31°
Dilation angle	3

Table 2: Caisson properties considered in this study.

Properties of caisson	Values
Material	Aluminum
Young's modulus MPa	69 MPa
Poisson's ratio, μ	0.32
Unit weight, γ kN/m^3	27 kN/m^3

(iv) No specific initial stress condition was assigned to the model. Only geostatic stresses and self-weight of the model was assigned. In a practical case, the caisson is sunk into the ground by driving. But for the simulation process, the caisson model was just embedded into the soil model which is done through embedded region option in constraints interface. As the soil model consists of sand, drained type of analysis is done by adopting Mohr–coulomb plasticity model.

In this study lateral displacement of 20 mm and the vertical settlement of 10 mm is applied on the top of the pile node and the lateral and vertical resistance for corresponding displacement and settlement is obtained from ABAQUS. Load and boundary condition of the root-caisson with soil model as shown in Figure 4.

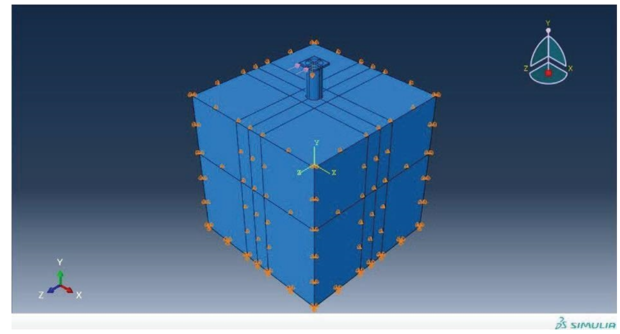


Figure 4: Boundary condition and loading of the caisson.

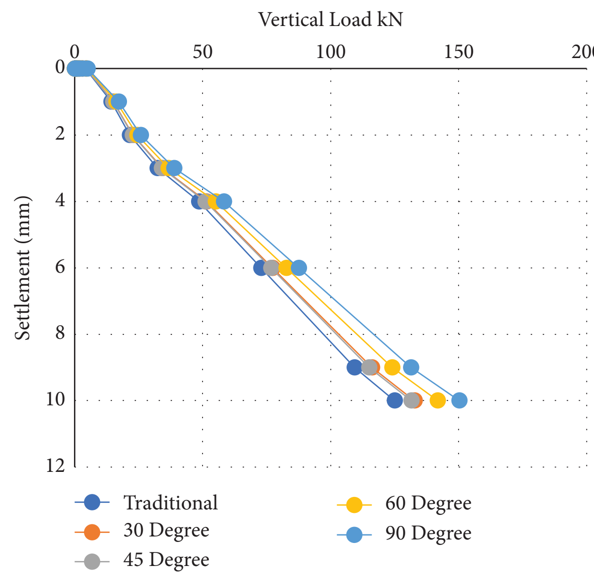


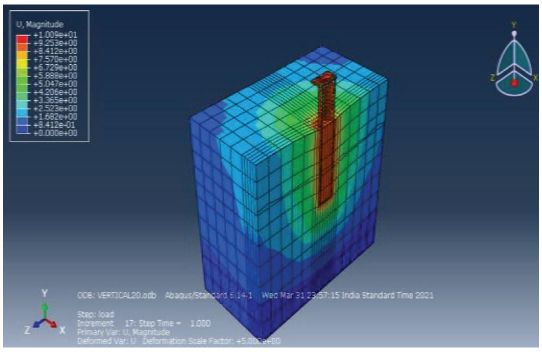
Figure 5: Load-deflection behaviour under vertical load.

3. Results and Discussions

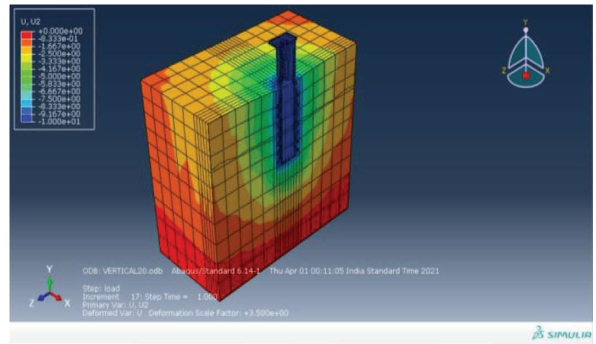
3.1. Caisson Behaviour under Vertical Load. According to IS codal provision, the ultimate vertical load will be taken based on the penetration value of 10% of the diameter of the caisson.

For the applied vertical settlement of 10 mm, the Load-Deflection graph has been shown in Figure 5. while comparing the vertical capacities of the traditional caisson with the rooted caisson, it can be seen that the vertical load bearing capacity has been increased from 124.93 kN to 150.24 kN during the ground deflections of 10 mm. The soil confined between the roots were also able to bear the load and distribute the load along the roots in addition to the caisson shaft. It is observed that the rooted caisson with a root inclination of 90° is having a higher vertical load bearing capacity compared to other degrees of root inclinations and traditional caisson.

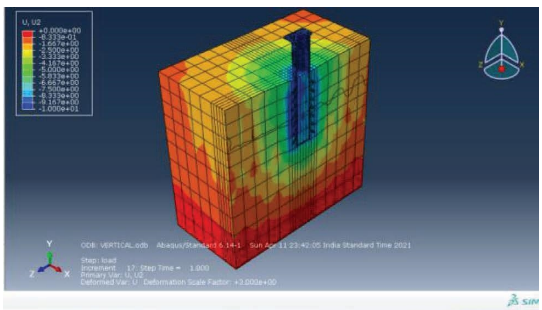
3.2. Verification by Comparison with Small-Scale Tests. The results obtained from the present study using Abaqus software, indicate an increase in vertical load bearing capacity, which is similar to the field experimental work of Lei et al, where the Load-Settlement curve is low for traditional caissons than for root caissons for the same vertical load [2]. It elucidates the point that the Root caisson foundations are more capable of bearing loads than traditional caissons. There was a very less displacement of the root-caisson foundation in comparison to that of the traditional caisson foundation. It is evident from this phenomenon that traditional caissons can have an improved vertical bearing capacity when there is a provision of fabricated roots, which can limit the vertical displacement of structures. One of the researchers Dhatrak et al. carried out a laboratory vertical load test on scale downed root caisson made of polymeric material with a diameter of 100 mm and height of 600 mm, as well as horizontal roots are made up of mild steel bars with different length to diameter ratios. In order to fix the roots over the caisson, holes were drilled over its surface. Model roots were provided with threaded ends that can be attached to the wall of a model caisson with nuts. With increased root lengths, Root-Caisson's vertical load capacity increased from 18% to 123% for 0.4 m length of roots [3]. This result can be somehow used to validate the result obtained from the current study on root caisson using ABAQUS software. In the present study, the entire caisson and root has been



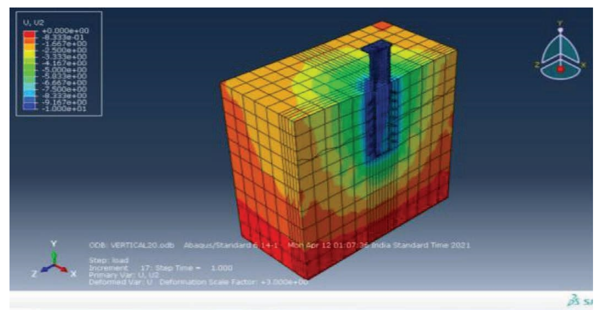
Traditional Caisson



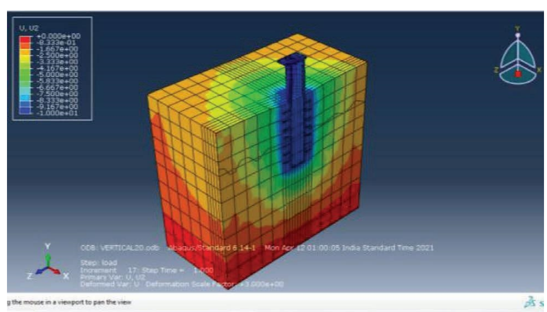
Root-Caisson with Root of 30°



Root-Caisson with Root of 45°



Root-Caisson with Root of 60°



Root-Caisson with Root of 90°

FIGURE 6: Displacement contours of caisson under vertical loading.

considered as an aluminium material with dimensions similar to the previous case. Also, the connections between the root and caisson were made as a welded connection. The loading parameters considered were similar to as the previous condition, the vertical load results show that the capacity of root caisson increases from 124.93 kN to 150.24 kN for the allowable ground deflections of 10 mm.

3.3. Analytical Results of Nonlinear Analysis. The visualization or output data is the evaluation outcome of the finite element nonlinear analysis. The postprocessing segment is the rendering of output in the form of coloured mapping of the root-caisson and traditional caisson. The finite element analysis is carried out on the proposed traditional caisson and root caisson with a different inclination of roots. The observations made from the analytical investigations are presented in the following sections. The parameters considered for the present study are as follows:

(i) Deflection/Settlement

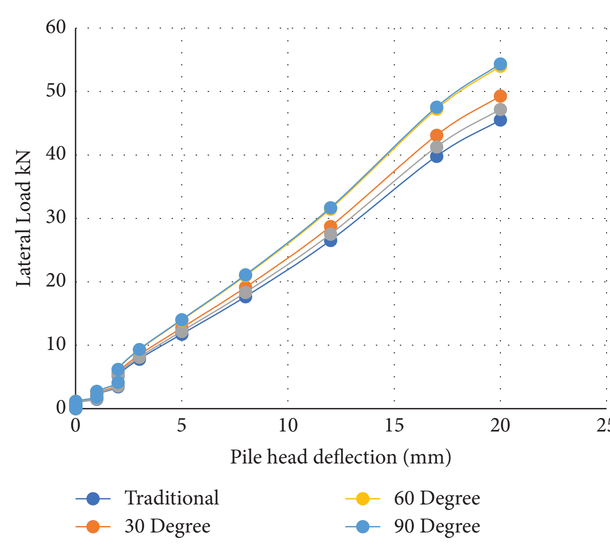
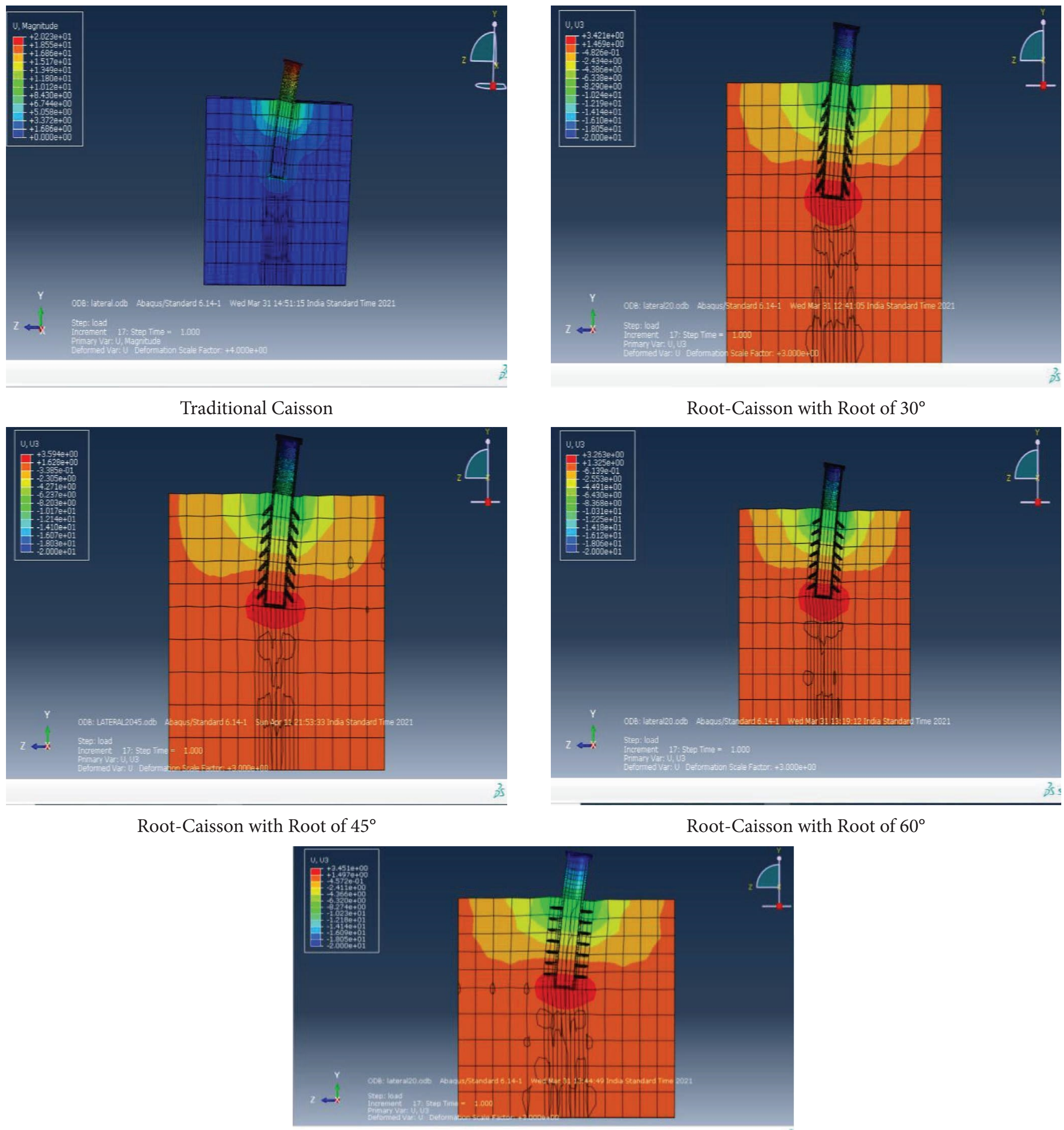


FIGURE 7: Load-deflection behavior under lateral load.



Traditional Caisson

Root-Caisson with Root of 30°

Root-Caisson with Root of 45°

Root-Caisson with Root of 60°

Root-Caisson with Root of 90°

FIGURE 8: Displacement contours of caisson under lateral loading.

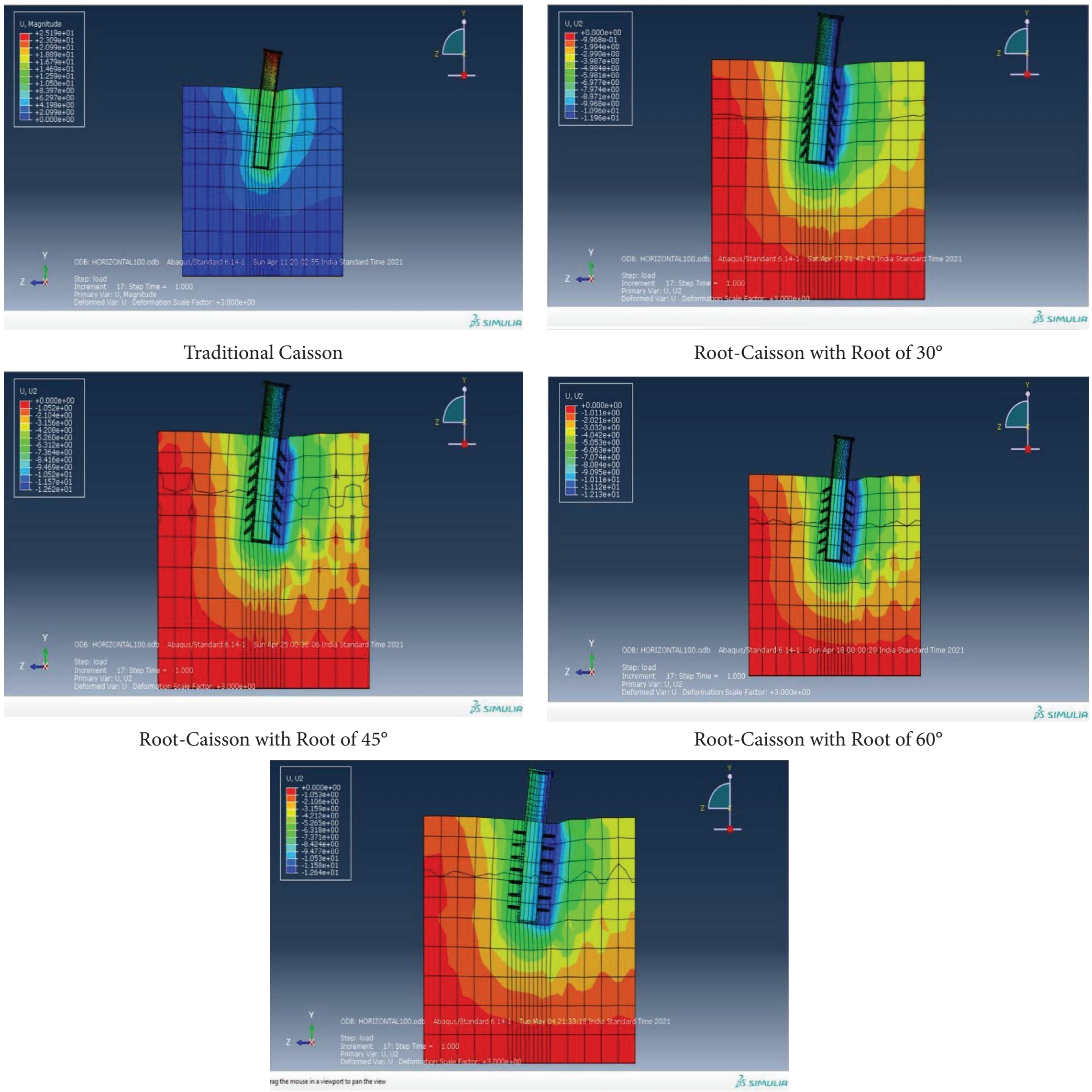
(ii) Reaction force of the section

3.4. Deflection/Settlement and Reaction Force.

3.4. Deflection/Settlement and Reaction Force. The deflections/settlement and reaction force for the traditional caisson and root-caisson foundation are discussed. A coloured mapping of the traditional caisson and root-caisson indicates the deflected/settlement shape and reaction force. The red colour indicates the maximum deflected/Settlement region and rection force region, maximum deflection occurs at the top of the caisson. Blue colour indicates the least deflection taking part in the root-caisson at most in the bottom of the caisson. The coloured deflected/settlement shape and reaction force of traditional caisson and root caissons under vertical loading condition is shown in Figure 6.

3.5. Caisson Behaviour under Lateral Load. In this study, as per Broms [15], lateral deflection at the ground level is taken as 20% of the diameter of the caisson.

For the applied pile head deflection of 20 mm, the Load-deflection graph has been shown in Figure 7. The lateral load bearing capacity of the caisson increases from 45 kN to 54 kN for the ground level deflection of 20 mm. It is observed that the rooted caisson with a root inclination of 90° is having a higher lateral load bearing capacity compared to other degrees of root inclinations and traditional caisson.



Traditional Caisson

Root-Caisson with Root of 30°

Root-Caisson with Root of 45°

Root-Caisson with Root of 60°

Root-Caisson with Root of 90°

Figure 9: Displacement contours of caisson under combined loading.

Moreover, the root caisson with 60° inclination shows similar load improvement as that of 90° root caisson. The coloured deflected/settlement shape and reaction force of traditional caisson and root caissons under lateral loading condition is shown in Figure 8.

3.6. Caisson Behaviour under Combined Load. For this study, a lateral load of 50 kN is divided into 20, 40, 60, 80, and 100% and is applied individually over a caisson head with varying axial load. Figure 9 represents the effect of combined loading on the caisson head in the sandy soil at the horizontal ground.

It is noticed from Table 3. that the ultimate vertical load bearing capacity of the caisson models with L/D of 4 is found to be increased marginally by about 20% at low constant horizontal load (0.2H) to high constant horizontal load (H). The higher percentage of load bearing capacity is due to the provision of roots at an angle of 90°, it offers more resistance than other degrees of root caisson and traditional caisson.

3.7. Effect of Spacing(S) on Load-Carrying Capacity. Analysis of caisson with 90° inclination with the same l/d ratio of roots and varied the spacing(S) between the roots as for 0.5 D, 0.6 D, and 0.75 D was considered. From Table 4. it was observed that for spacing of 0.75, 0.6, and 0.5 times the diameter of the caisson, the number of floors obtained was 5, 6, and 7 with a total of 20, 24, and 28 roots in it. The load bearing capacity of the caisson with 50 mm spacing between the floors of roots shows a higher result than the caisson with 60 mm and 75 mm spacing, it indicates that if the spacing between the roots increases, and there is a considerable decrease in the load bearing capacities.

Table 3: Ultimate vertical load measured with and without constant lateral load.

Lateral load	Ultimate vertical load kN for L/D = 4						
	Conventional type	30°	45°	60°	90°		
					S = 0.5 D	S = 0.6 D	S = 0.75 D
0H	124.93	132.69	131.51	141.83	150.24	149.67	148.57
0.2H	125.98	133.77	132.60	142.84	151.33	150.76	149.69
0.4H	127.04	134.74	133.68	143.85	152.41	151.85	150.81
0.6H	128.09	135.77	134.77	144.85	153.50	152.93	151.93
0.8H	129.14	136.80	135.86	145.86	154.58	154.02	153.05
H	130.19	137.82	136.94	146.86	155.67	155.10	154.16

Table 4: Ultimate root caisson capacity under various spacing condition.

Description			Vertical load bearing capacity kN	Lateral load bearing capacity kN	Combined load bearing capacity kN
Spacing between roots(S)	No. of roots	Floors			
S = 0.75 D	20	5	148.57	53.61	154.16
S = 0.6 D	24	6	149.67	54.25	155.10
S = 0.5 D	28	7	150.24	54.37	155.67

4. Conclusion

The lateral and vertical load bearing capacity of root-caisson with different inclinations of roots are 30°, 45°, 60°, and 90° and traditional caisson are determined using ABAQUS. The following conclusions are drawn based on the present study.

(i) The ultimate load bearing capacity of caisson with 90° roots is (from 124.93 kN to 150.24 kN) 20% higher than traditional caisson it indicates that the root-Caisson foundation has a higher vertical and lateral load bearing capacity as compared to that of traditional Caisson foundation due to the provision of roots.

(ii) The result shows that the roots provided along the caisson shaft and the soil in-between the roots share the externally applied loads along with the caisson.

(iii) The optimum angle of inclination for the roots of root-caisson is 90° in both vertical, lateral, and combined loading using ABAQUS software.

(iv) The 60□ inclined root caissons show higher lateral load bearing capacity similar to 90° inclined root caisson.

(v) The load bearing capacity of caisson with 90° roots is 13%, 14%, and 6% higher than 30°, 45°, and 60° roots, respectively. It shows that the caisson with horizontal roots is having more vertical and lateral load bearing capacity as compared to the caisson with inclined roots.

(vi) A caisson with 7 floors of roots has a higher load bearing capacity than a caisson with 6 and 5 floors of roots. It was observed that as the number of floors and roots increased, the Root Caisson foundation's vertical and lateral load bearing capacity increased.

(vii) The load bearing capacity of caisson with 50 mm spacing between the floors of roots shows a higher load taken than caisson with 60 mm and 75 mm spacing it indicates that the increase in spacing between the floors of roots, decreases the lateral and vertical load capacity of Root Caisson.

(viii) Horizontal roots significantly increase the lateral and vertical load bearing capacity of root-caisson due to the increase of passive resistance for horizontal root-caisson as compared to inclined root caisson.

Further research on the load bearing capacity of a root caisson can be carried out by varying the patterns of roots, directions of loading, and variations in the eccentricity of loading conditions.

Data Availability

The underlying data supporting the results of this study are included within this paper.

Conflicts of Interest

The authors declare that they have no known conflicts of interest.

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