Seismic Analysis of Caisson Foundation

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***Abstract*— Caisson foundations are extensively used as supports and anchors for major structures especially bridges in soft soils. This study involves seismic analysis of caisson foundations in cohesive soil under lateral load and overturning moment. A simplified model of caisson is developed in ANSYS software and nonlinear static pushover analysis is performed. A caisson with pier column is modeled and a mass is attached to the top of pier column. Rotational springs are attached to both caisson and deck mass. This arrangement constitutes a simplified model. Different simplified models are prepared with changes in spring stiffness, and a most effective model is selected. For this effective model, the pier height is varied and analysed**.

***Keywords*—Caisson Foundation; Nonlinear Static Analysis; Cohesive Soil; Lateral Load; Overturning Moment.**

I. INTRODUCTION

Caisson foundations are widely used as supports and anchors for major structures in soft soils. Mainly caissons are used for supporting bridges, transmission towers etc. In cases where the span of the bridge is very much greater and the structure becomes very heavy, in such situations a massive foundation called caisson is provided. But this massive dimension of caisson does not guarantee seismic resistance. As a result of their geometry and stiffness characteristics, the mechanisms of load transfer from the superstructure to the surrounding soil become complex. A study of the behavior of caisson when subjected to horizontal load is essential to understand the foundation behavior. For analysis, the caisson- soil- pier system is simplified. Finite element simplified model is developed which will allow for realistic representation of complex soil-structure interaction effects associated with these foundation elements. The main advantages of using simplified model for analysis include: (a) simplicity, (b) computational cost effectiveness and (c) versatility to describe the observed response. Caissons are highly versatile in constructability for a wide variety of soil formations, and can be installed in virtually any soil type including residual soils, soft soils and marine sites. Even further, since no dewatering is necessary during construction, caissons are particularly advantageous at soft sites or sites where excessive groundwater is considered to be critical for the selection of the excavation and support method. Large diameter caisson foundations are used for the most part as bridge foundation elements, as well as deep-water wharves, and overpasses.

In this thesis work a simplified model of caisson-pier system is developed. The major components of model are soil (cohesive), caisson, pier column and mass. Soil is modeled as spring, and the stiffness of soil is given to rotational spring. The pier column is modeled as a beam element and the mass of deck is attached to the pier column. A horizontal load and overturning moment is applied at the top of the pier. For deck stiffness rotational spring is attached with the mass. In 2014, Athanasios Zafeirakos and Nikos Gerolymos conducted an analytical study involving nonlinear static analysis of caissons and they proposed a methodology for seismic capacity design [1]. Gazetas. G and Varun Assimaki D (2009) developed an analytical model that accounts for the multitude of soil resistance mechanisms mobilized at their base and circumference, while retaining the advantages of simplified methodologies for the design of non-critical facilities [6].

II. SELECTION OF IDEALISED MODEL

A. *Finite Element Modeling*

The nonlinear response under lateral monotonic and slow-cyclic loading of caisson foundations supporting bridge piers in cohesive soils is investigated. The caisson under study is supporting a reinforced concrete arch bridge; the bridge has a total length of 200m and a central span of 90m. The bridge deck was constructed by the cantilever method and is rigidly connected to the piers. The caisson is surrounded by soil and the load transfer from the deck is through the pier column. Here the caisson is a concrete square structure having a size of 10m x 10mx 10m. The caisson material is modeled as isotropic linear elastic, with a unit weight of γ=25 kN/m^3, a Young's modulus of Ec=3 x 10^8 kPa and a Poisson's ratio of ν_c=0.15. The concentrated mass on pier column is 2700 kg. Two layers of soil are modeled, assuming homogeneous elastic soil conditions. Top layer has a depth of 6m and for bottom layer 14m. The size of the finite element mesh is 5Bx5Bx5B where B is the width of caisson. The element chosen is SOLID 187 for both caisson and soil and BEAM 188 for pier column.

TABLE I. PROPERTIES OF MATERIALS

Property	Concrete	Top Soil	Bottom Soil
Density	2548 kg/m^3	1723.65 kg/m^3	1814.37
Modulus of elasticity	3 x 10^{11} Pa	97.5 MPa	195 MPa
Poisson's ratio	0.15	0.25	0.25
Bulk modulus	1.4286 x 10^{11} Pa	65 MPa	130 MPa
Shear modulus	1.3043 x 10^{11} Pa	39 MPa	78 MPa

In this study a simplified model of caisson- soil- pier system is modeled and four idealized versions of actual system are considered with respect to the top (pier- bridge- deck support connection) and bottom (foundation compliance) boundary conditions.

1. A top free to rotate column (appropriate for modeling the lateral response of relatively long-spanned bridges, or when the bridge columns and beams are connected through a hinge) fixed at its base.
2. A beam column fixed at its base, the motion of which is hampered at its top against rotation via a rotational spring k_R representing the pier-to- deck connection rigidity.
3. Similar to model 2, additionally four rotational springs on the four surfaces of caisson (k_H) and a rotational spring at the bottom (k_M).
4. Similar to model 3, but with consideration of linear stiffness matrix for foundation compliance, i.e., k_H, k_M, k_{MH} (on bottom edges of caisson).
   Out of which the best model is chosen and analysis is carried out for that model for different pier heights 6m, 17m, and 55m. The value of $K_{H,}$ K_M, and K_{MH} are found by equations (2),(3) and (4).

B. Properties of Pier Column

The pier columns are modeled with 3-D beam elements, with elasticity modulus E_c=3 x10^8 kPa and ν_c=0.15. The geometric properties of the piers, namely the cross-sectional areas (A: m^2) and moments of inertia (I: m^4), are given in Table2. To investigate the effect of pier-to deck stiffness on the response of the foundation, the stiffness of the rotational spring, $K_{R,}$ was appropriately modified so that the stiffness ratio,

$K_{ratio} = K_R/(4EcI/H)$ (1)

where, $(4EI_c/H)$ is the flexural stiffness of the column, yields the following values: K_{ratio}=0.1,0.25,0.5,1 for every case examined. The shear modulus of rock at very small deformations is estimated to G_0 =1 GPa.

$K_H = 9.4G_0B;$ (2)

$K_M = 10.8G_0B^3;$ (3)

$K_{MH} = -6.3G_0B^2$ (4)

where, B is the width of square caisson, B=10m. On substituting this in above equations we get,

$K_H = 9.4 \times 10^{10}$ N/m

$K_M = 10.8 \times 10^{12}$ N/m

$K_{MH} = -6.3 \times 10^{11}$ N/m

TABLE II GEOMETRIC PROPERTIES OF PIER COLUMN

H (m)	A (m^2)	I (m^4)
6	13.85	3.98
17	22.90	15.27
55	40.72	41.74

TABLE III VALUES OF K_R FOR DIFFERENT K_{RATIO} AND PIER HEIGHT

H (m)	K_{ratio}= 0.1	K_{ratio} =0.25	K_{ratio} =0.5	K_{ratio} =1
6	7.96 x 10^{10}	1.99 x 10^{11}	3.98 x 10^{11}	7.96 x 10^{11}
17	1.078 x 10^{11}	2.7 x 10^{11}	5.4 x 10^{11}	10.8 x 10^{11}
55	9.12 x 10^{10}	2.28 x 10^{11}	4.56 x 10^{11}	9.12 x 10^{11}

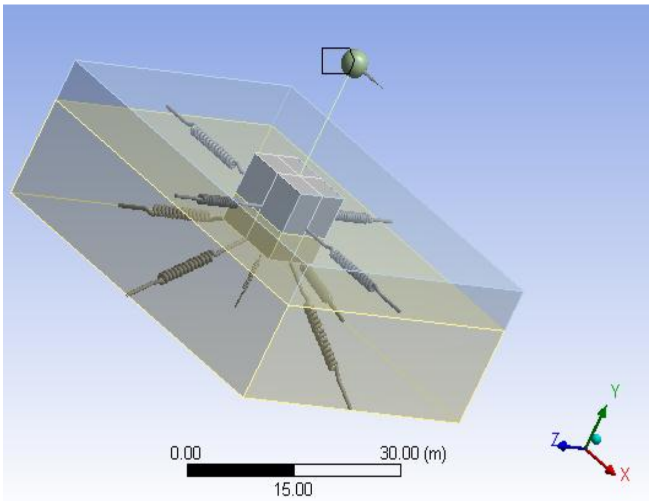

Fig. 1. Simplified model 4 (For 6m pier height and K_{ratio}= 0.1)

TABLE IV ANALYSIS RESULTS

Model	Load carrying capacity (%)	δl_{total} (m)	σ on caisson (Pa)	δl on pier (m)	Axial force on pier (kN)	M (Nm)	Θ (rad)
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
I	54%	11.2	1.6x10^7	11.2	2.11 x10^{-8}	1.4 x10^8	0
II	71%	1.14	3.5x10^7	0.06	82.06	2.4 x10^6	0
III	98%	0.24	2.56 x10^7	98 x10^{-5}	61.07	3 x10^5	0.033
IV	100%	0.14	2.49 x10^7	19 x10^{-5}	1.547	5 x10^7	0.019

The table IV shows the results of different models for 6m pier height and K_{ratio}= 0.1, representing (column1) load carrying capacity, (2) total deformation, (3) stress on caisson, (4) deformation on pier, (5) axial force on pier, (6) total moment, (7) rotation angle in radians. On comparing the results, the load carrying capacity of model 4 is more than model 1. For second model only k_R contribute the stiffness, so the load carrying capacity for model 2 is less. Model 4 is transferring the load into the soil through spring, so the load on the pier is less and thus the deformation will be less. The model 4 is the best model which is selected as the idealized simplified model.

Rui Zhong and Maosong Huang (2014) introduced a simplified method with a dynamic Winkler model to study the seismic response of composite caisson– piles foundations [2]. Juan M.Mayoral and Miguel P.Romo (2014) conducted numerical study to evaluate the seismic performance of massive foundations [3].

III. NONLINEAR STATIC ANALYSIS

The whole soil–foundation–superstructure system is then subjected to lateral loading at the deck level. Nonlinear static analysis is carried out using idealized simplified model. The values of ultimate lateral load is Q_u= 44 x 10^6 N and overturning moment is M_u= 430 x 10^6 Nm. These load and moment were applied at the mass on top of the pier column. The structure is analyzed for this slow cyclic loading and overturning moment. The analysis results of model with 6m pier height and K_{ratio}= 0.1 are as follows,

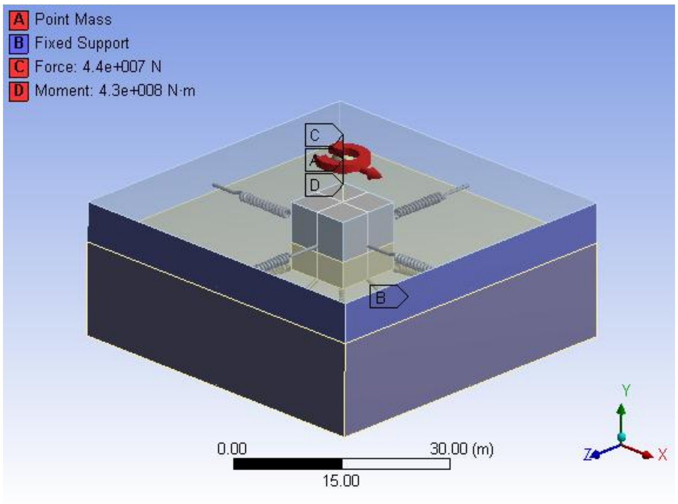

Fig. 2. Applying moment and horizontal load on the mass

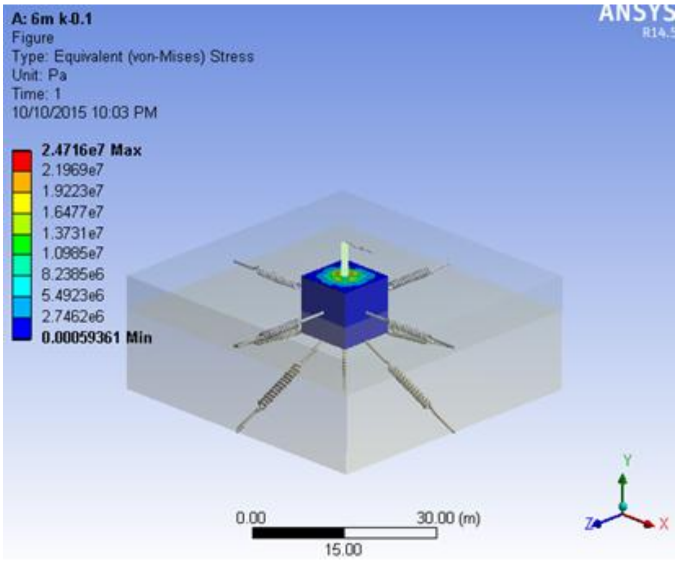

Fig. 3. Stress on caisson

Table V Total Bending Moment With Respect To Time

Time [s]	Minimum [N·m]	Maximum [N·m]
0.2	1588	4.2467e+006
0.4	6351.2	8.4927e+006
0.7	19448	1.4861e+007
1.	39685	2.1227e+007

The results of simplified model with different pier heights are analysed and compared. As the height of the column varies, the cross-sectional area and moment of inertia of pier column also changes. The short columns can carry more load and it is safe on comparing the results. If the structure is over designed it can carry more load, if it is under designed it is not sufficient to carry load.

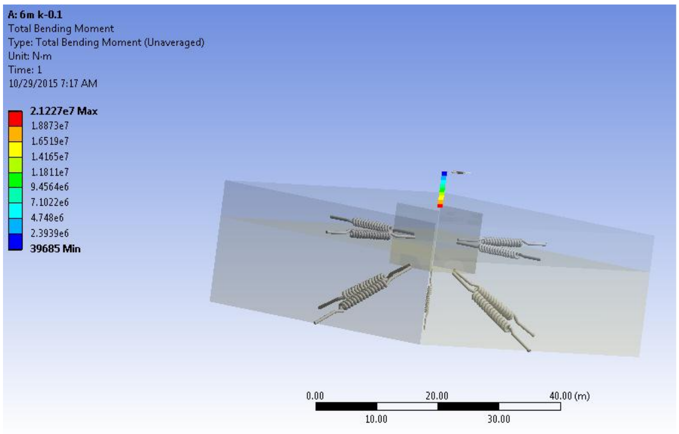

Fig. 4. Bending moment diagram

We can plot graphs based on the results obtained from analysis. From the graphs, 6m pier column is giving good results when compared to other two pier heights. So it is concluded that short columns behaves effectively when load coming on it.

TABLE VI RESULTS OF STATIC ANALYSIS

Ht. of the pier	K_{ratio}	δl_{total} (m)	δl on pier (m)	σ on caisson (Pa)	Axial force on pier (N)	M (Nm)	Θ (^{0})
6m	0.1	0.00935	5.39 x10^{-4}	2.7 x10^7	352.6	2.1 x10^7	0.079
	0.25	0.00928	2.77 x10^{-4}	2.5 x10^7	130.5	1.3 x10^7	0.079
	0.5	0.00925	2.62 x10^{-4}	2.5 x10^7	76.96	1.04 x10^7	0.079
	1	0.00924	2.59 x10^{-4}	2.5 x10^7	54.48	8.94 x10^6	0.079
17m	0.1	0.0092	4.1 x10^{-4}	2.538 x10^7	19.75	6.6 x10^6	0.079
	0.25	0.00918	3.05 x10^{-4}	2.544 x10^7	1.96	4.5 x10^6	0.079
	0.5	0.00918	3.08 x10^{-4}	2.546 x10^7	-3.051	3.8 x10^6	0.079
	1	0.00918	3.1 x10^{-4}	2.547 x10^7	-5.349	3.4 x10^6	0.079
55m	0.1	0.009	1.11 x10^{-3}	6.596 x10^6	-21.7	1.254 x10^6	0.074
	0.25	0.00933	1.03 x10^{-3}	6.595 x10^6	-22.97	9.606 x10^5	0.077
	0.5	0.00933	1.01 x10^{-3}	6.595 x10^6	-23.29	8.674 x10^5	0.077
	1	0.00932	1.02 x10^{-3}	6.595 x10^6	-22.96	9.606 x10^5	0.071

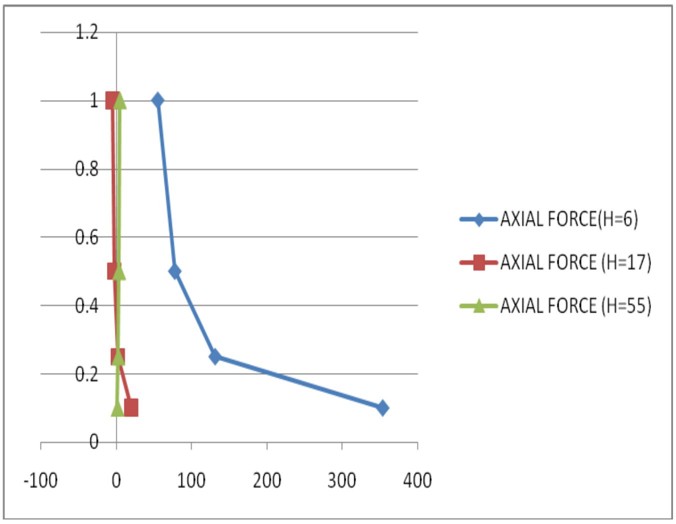

Fig. 5. Axial force diagram for different K_{ratio}

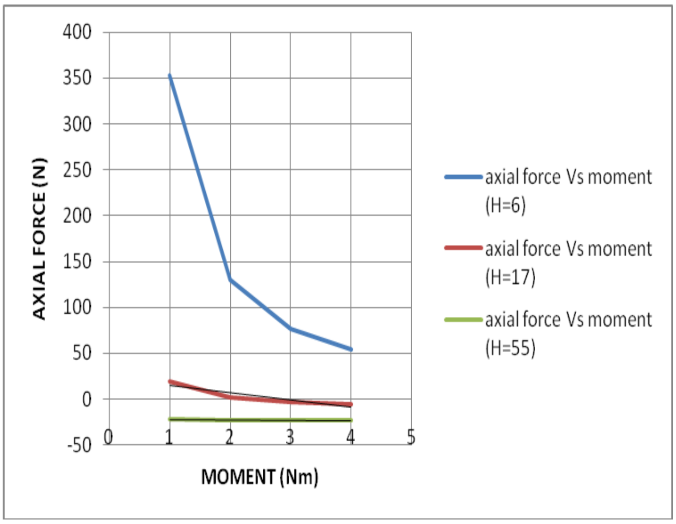

Fig. 6. Bending moment diagram for different K_{ratio}

IV. CONCLUSIONS

A simplified model is analysed using ANSYS software. The pier height (H), the embedment ratio of the caisson (D/B) and the pier-to-deck joint rigidity (K_R) varied parametrically, with the latter being modeled by a rotational spring at the deck level. The soil is also modeled as rotational springs. The foundation–superstructure systems were then subjected to lateral monotonic and slow-cyclic loading at the deck level. The load transfer is from pier to the caisson then to the spring. The spring stiffness value affects the pier height. In the case of pier column, the axial force on the pier is more at the top. The load carrying capacity is more for pier height=6m. The deformation on the pier increases with increase in pier height. The stiffness value of spring is changed and analysed. The response of structure is different for different stiffness ratio. The rotational stiffness on the deck mass is different for different stiffness ratios. It is concluded that the model 4 is proved as an idealized simplified model where the pier should not be too long or too short.

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