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Pseudo-static analysis of caissons to determine critical loading ratio

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ABSTRACT: Caisson foundations are massive foundations designed to support excessive vertical as well as lateral loads. Loads such as dead load of structure, live load of vehicles, buoyancy and vertical inertial forces due to earthquakes constitute vertical forces and forces caused by water, wind, soil and earthquakes account for horizontal forces. The relative magnitude of these forces may have a bearing on the response of the caissons under a given load combination. Based on this premise, the current study is carried out to determine the value of ratio of horizontal load to vertical load which gives optimum values of caisson responses like maximum bending moment. In the present study a rigid caisson embedded in cohesionless soil with an embedment ratio (ratio of embedment depth to diameter of caisson) of 3 is considered. The numerical modeling is done using Finite Element Analysis based software ABAQUS. Based on the analyses, the value of loading ratio for which magnitude of maximum bending moment comes out to be minimum is determined. This study will help in deciding the weight and thickness to maintain the obtained value of loading ratio of caissons in order to minimize the value of maximum bending moment.

1 INTRODUCTION

Caissons or well foundations are enormous sub-structures which are used to resist a variety of load combinations and transfer them to soil below. By virtue of their large mass, they can resist high magnitudes of uplift forces as well as lateral loads. This makes them ideally suited to be used as pier foundation for a bridge over a water body or otherwise. The large diameter and depth of a caisson provide it sufficient stiffness to resist loads transmitted by bridge piers.

Basic diagram depicting different components of a caisson has been shown in Figure 1.

Load is transmitted from superstructure such as bridge through pier. The pier is supported by RCC slab which serves as well cap. The well cap in turn transfers the load to well steining which is also the main body of the well. Well is generally sunk into the ground under its own weight which is facilitated by sharp metal edges at its bottom known as cutting edge. Well curb acts as the junction between well steining and cutting edge. As soon as the well is sunk to the desired depth, its bottom portion is plugged with concrete. Sand is filled in the well above the bottom plug. This sand filling serves twin purposes of providing extra mass to the well for resisting uplift and also provides much better load transfer. After sand filling is done, top of well is plugged with concrete as well and overlain by well cap which supports the superstructure. It is assumed that net lateral load Q_o and moment M_o acts at scour level. Under the action of these loads, lateral soil reaction σ_x acts along the periphery of the caisson. In addition to this vertical shear traction τ_{xz} and horizontal shear traction τ_{xy} and τ_{yx} act along the periphery of the caisson. Bending stresses shown inside the caisson are also developed. Caisson tilts about a point above the base of caisson and the lateral soil pressures distribution is in accordance with the tilt of the caisson.

The first work in this field was done by Terzaghi (1943) who proposed to analyse well as a free, rigid bulkhead subjected to lateral load. Pender (1947) suggested analysis with the

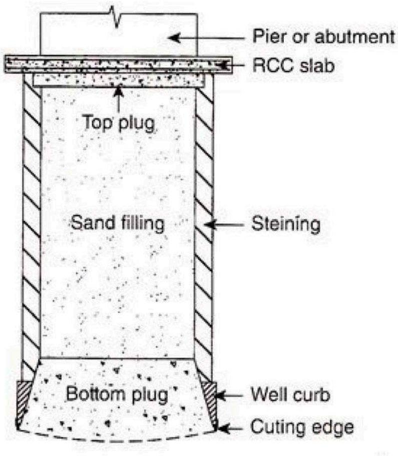


Figure 1. Various components of a typical well foundation (www.soilmanagementindia.com)

assumption that soil around the pier behave like linear springs with stiffness increasing with depth. Later Banerjee and Gangopadhyay (1960) formulated equations for lateral stability of wells by making use of concepts from both Terzaghi's (1943) and Pender's (1947) analysis. Sharda (1975) performed a series of lab and field tests by applying a combination of loads for carrying out a parametric study of wells. The author also proposed analytical method for anlysing lateral resistance of wells considering the non-linear behaviour of soil. Dominguez (1978) suggested boundary element solution for rectangular foundations in half space. Mitta and Luco (1989) gave hybrid boundary element and finite element for square foundation embedded in halfspace. Harada et al. (1981) combined the concepts of Tajimi and Novak to develop an approximate analytical solution. Novak assumed plane strain conditions for his analysis which gave results to a certain degree of accuracy. Gerolymos and Gazetas (2005) performed analytical study of rectangular and circular rigid caisson in linear soil using elastodynamic theory and derived closed form solutions for springs and dashpots. The authors further extended this study to develop a non-linear Winkler spring method for static, cyclic and dynamic response of caisson foundation. Subsequently, the authors compared their model using results from 3D finite element analysis and model tests in the field.

2 NUMERICAL MODELING OF LATERALLY LOADED CAISSON

A 6m × 6m square caisson with depth of embedment of 18m is installed in granular soil with angle of friction of 33.8°. The soil properties considered in the present study have been given Table 1. The well properties used in the present study has been mentioned in Table 2. Allowable bearing pressure was determined which gave the allowable vertical load (Q_a) as 56500MN. Allowable bearing pressure has been defined as per recommendations of IS: 3955 (1967). The code recommends elastic theory for design of wells. So, allowable bearing pressure corresponds to yield stresses factored with appropriate factor of safety. IS code has mathematically defined allowable bearing pressure (Q_a) as:

$$Q_a = 5.4N^2B + 16(100 + N^2)D \tag{1}$$

where, Q_a is allowable bearing pressure (kg/m^2), N is corrected value of standard penetration resistance, B is smaller dimension of well section(m) and D is depth of foundation below scour level(m).

Table 1. Soil properties considered in the present study

Soil Properties	Values
Elastic modulus (MPa)	100
Poisson's Ratio [μ]	0.3
Unit weight [γ] (kN/m^3)	16.58
Friction Angle (°)	33.8

Table 2. Caisson properties considered in the present study

Pile Properties	Values
Grade of Concrete	M25
Young's Modulus [E_p] (MPa)	25000
Poisson's Ratio [μ]	0.2
Unit weight [γ_c] (kN/m^3)	25

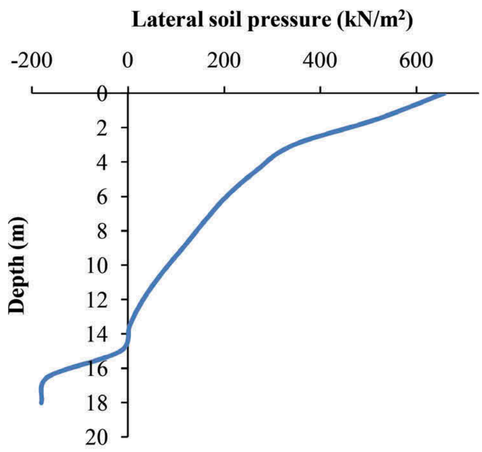
Caisson was embedded in soil strata of dimensions 60m × 60m×60m and soil non-linearity was also taken into account by considering stress-deformation results of triaxial tests conducted on the above soil. Plastic strain values for yield stresses at different stages of loading as obtained from triaxial test has been incorporated in the analysis to consider material behavior post yielding. 8-noded 3D hexahedral elements were used to model both soil and caisson. Encastre boundary conditions (U1= U2= U3= UR1= UR2= UR3= 0) has been adopted in the current study and these conditions gave very good agreement of results with the experimental results of Sharda (1975). U1, U2, U3 are the displacements in X, Y and Z directions respectively whereas UR1, UR2 and UR3 are the rotations in the corresponding directions. Mohr-Coulomb model has been adopted for numerical modeling in the current study. Soil- caisson interface friction angle has been mentioned in the interface properties assumed same as the soil friction angle and "hard contact" has been established to use the classical Lagrangian multiplier method of constraint enforcement. Also, separation after contact has been allowed to better simulate active conditions of soil pressure. Vertical loads (V) of magnitude 0, $Q_a/4$, $Q_a/2$, $3Q_a/4$ and Q_a were applied. For each magnitude of V, lateral loads of magnitude V/4, V/2, 3V/4 and V was applied on caisson at a height of 24m above the base of well. For V=0, lateral loads of magnitude 500kN, 1000kN, 1500kN and 2000kN were applied.

3 RESULTS AND DISCUSSIONS

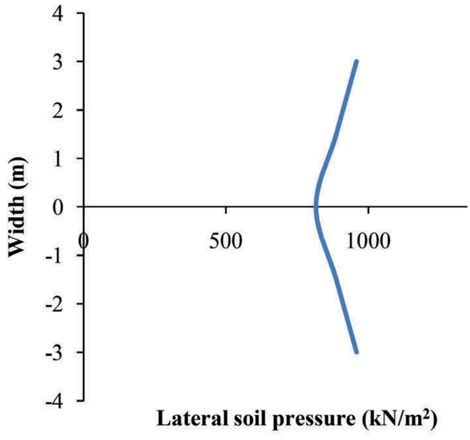
The response of vertical and lateral load on caisson was analyzed using finite element based software ABAQUS. Lateral soil pressure, side friction and maximum and minimum soil pressure at base of well were obtained. These data were used to obtain the magnitudes of net moment acting on well at any depth. Well displacements (tilt of well) and point of rotation of well were also reported.

3.1 *Effect on lateral soil pressure*

A typical representation of variation of net lateral soil pressure along the depth is shown in Figure 2(a). The variation along width of caisson has been represented in Figure 2(b). These values were then used to determine section forces which were further used to calculate restoring moments which in turn gives net moment at any point. The net maximum moment for all



(a)



(b)

Figure 2a. Variation of lateral soil pressure along depth

Figure 2b. Variation of lateral soil pressure along width

cases were calculated and presented. Along the width, the lateral soil pressure is maximum at the ends and reduces non-linearly towards centre.

3.2 *Effect on maximum and minimum base pressure*

The maximum and minimum base pressures for each case were normalized with respect to vertical loads. Normalized maximum and minimum base pressures for different magnitudes of vertical loads and lateral loads have been presented in Tables 3 and 4 respectively. Maximum base pressure has been represented as $\sigma_{b,max}$ and minimum base pressure has been represented as $\sigma_{b,min}$.

Table 3. Normalized maximum base pressure variation with vertical and lateral load

		Lateral Load Q			
	V	V/4	V/2	3V/4	V
$(\sigma_{b,max}/V)*1000$ [kN/m^2/kN]	$Q_a/4$	14.447	14.338	14.943	15.693
	$Q_a/2$	14.125	13.565	14.109	15.140
	$3Q_a/4$	14.067	13.312	14.209	14.411
	Q_a	13.185	12.452	12.462	13.630

Table 4. Normalized minimum base pressure variation with vertical and lateral load

		Lateral Load Q			
	V	V/4	V/2	3V/4	V
$(\sigma_{b,min}/V)*1000$ [kN/m^2/kN]	$Q_a/4$	2.825	2.084	1.200	0.269
	$Q_a/2$	2.821	2.103	1.068	−0.130
	$3Q_a/4$	2.793	2.146	0.958	−0.682
	Q_a	2.780	2.187	0.800	−0.544

Table 5. Normalized maximum moment variation with vertical and lateral load

	V	Lateral Load Q V/4	V/2	3V/4	V
$(M_{max}/V)*1000$ [kN-m/kN]	$Q_a/4$	2.745	5.572	8.378	11.163
	$Q_a/2$	2.761	5.609	8.493	11.507
	$3Q_a/4$	2.742	5.646	8.748	12.029
	Q_a	2.834	5.83	8.906	12.136

It was observed that as the vertical load increases, normalized maximum base pressure decreases and as the lateral load increases, the normalized maximum base pressure first decreases and then increases. Normalized minimum base pressure also decreases with increase in both vertical and lateral load.

3.3 *Influence on maximum moment*

Maximum moment values normalized with respect to vertical load has been presented in Table 6. It is evident from the table that as the loading ratio (ratio of lateral load to vertical load) increases, there is marked increase in normalized maximum moment value. In addition to this, slight increase in normalized maximum moment value is also observed when the vertical load is increased.

3.4 *Influence on well displacements*

Well displacements along the depth of well were determined and plotted as shown in Figure 3. These data were used to calculate tilt of well and the point of rotation of well. The variation of tilt (θ) normalized with respect to vertical load has been expressed in Table 6. One obvious conclusion that can be drawn is that the magnitude of normalized tilt increases with increase in lateral load. However, normalized tilt of well initially decreases marginally with increase in vertical load but at higher magnitude of vertical load when yielding of surrounding soil is triggered, the tilt of well increases significantly.

Table 6. Variation of normalized tilt of well with vertical and lateral load

	V	Lateral Load Q V/4	V/2	3V/4	V
$(\theta/V)*10^6$ [°/kN]	$Q_a/4$	2.714	5.821	9.046	12.41
	$Q_a/2$	2.606	5.556	8.692	12.22
	$3Q_a/4$	2.563	5.493	8.941	14.081
	Q_a	2.552	5.634	10.305	19.695

Table 7. Variation of depth of point of rotation of well with vertical and lateral load

	V	Lateral Load Q V/4	V/2	3V/4	V
Depth (m) [m/kN]	$Q_a/4$	13.485	13.269	13.196	13.138
	$Q_a/2$	13.852	13.491	13.431	13.34
	$3Q_a/4$	13.902	13.626	13.598	13.559
	Q_a	13.995	13.74	13.757	13.82

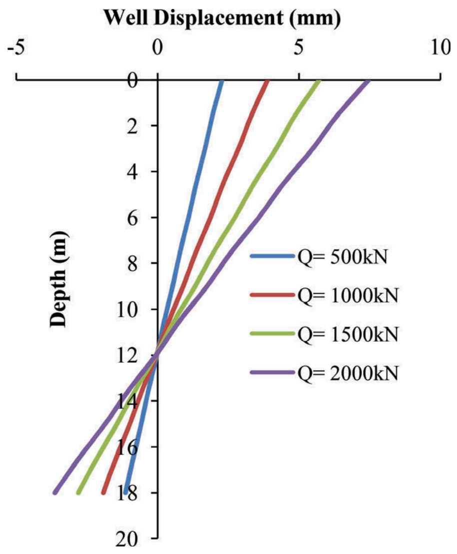


Figure 3. Caisson displacement in absence of vertical load (V = 0)

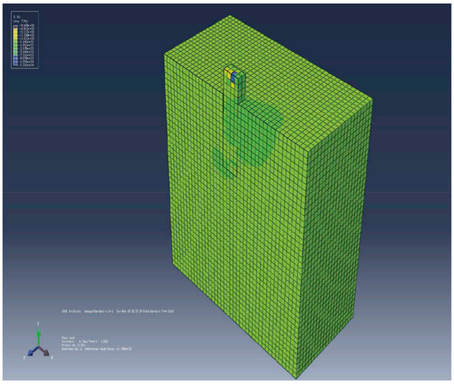


Figure 4. Lateral stress distribution contour

Also, the point of rotation of well is determined as the point where net horizontal force is zero. The variation of depth of point of rotation with loading has been shown in Table 7. It can be observed from the table that as the vertical load increases the depth of point of rotation of well also increases which suggests greater stability of caisson.

The stress distribution over entire soil strata appears uniform as the green portion lies in the region where magnitude of stress changes from positive to negative. Therefore, regions with low positive and negative magnitude of stress as well as that of zero stress are represented by the same colour of spectrum.

4 CONCLUSIONS

In the current study, a 3D model of a square caisson embedded in soil strata created and analyzed using finite element based software ABAQUS. Variation in vertical and lateral load acting on caisson was made in order to obtain the best loading combination on the caisson in order to minimize stresses and moments for any general loading and geometry of caisson. Since the caisson responses have been normalized with respect to vertical load, the trend of responses should be same for the given soil type (cohesionless soil) irrespective of dimensions of caissons and height of lateral load application. Following conclusions could be drawn from the current study.

- As the vertical load increases, normalized maximum base pressure decreases and as the lateral load increases, the normalized maximum base pressure first decreases and then increases. This behavior could be attributed to the higher bending stresses developed in the caisson because of excessive magnitudes of lateral load. Normalized minimum base pressure also decreases with increase in both vertical and lateral load. Ideal loading conditions would be such which give minimum value of maximum base pressure and maximum value of minimum base pressure. This can be achieved by minimizing the value of loading ratio while keeping the value of vertical load as large.
- As the loading ratio increases, there is marked increase in normalized maximum moment value. In addition to this, slight increase in normalized maximum moment value is also

observed when the vertical load is increased. This behavior is direct result of the higher magnitudes of lateral loads which give high magnitude of moments. This criteria also suggests the loading ratio to be kept as low as possible. The effect of vertical load is nominal, so it can be kept as any convenient value.

- The magnitude of normalized tilt increases with increase in lateral load which is a direct consequence of the lateral load. However, normalized tilt of well initially decreases marginally with increase in vertical load but at higher magnitude of vertical load when yielding of surrounding soil is triggered, the tilt of well increases significantly. This criterion suggests lowest possible magnitude of loading ratio while keeping the magnitude of vertical load in an intermediate range.
- As the vertical load increases the depth of point of rotation of well also increases which suggests greater stability of caisson. This criterion also recommends the loading ratio to be minimized. According to this criterion, increasing the magnitude of vertical load to reduce loading ratio is a better option.

In conclusion the caisson responses suggest that the ratio of lateral load to vertical load should be kept to a value as low as possible which could be achieved by increasing the magnitude of vertical load to a high value which results in soil pressure less than allowable bearing pressure.

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