Comparative Studies on Behaviour of Caisson Foundations under Static and Seismic Conditions

Études comparatives sur le comportement des fondations de caissons dans des conditions statiques et sismiques

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ABSTRACT: Several proposed analytical methods and numerical model studies to simulate the caisson-soil interactions have been reviewed and a comparative study has been presented. In published literature, researchers had attempted to capture the stress distribution at the caisson foundation-soil interface which showed significant sharing of loads by both caisson base and circumference. Present study shows that the position of the point of rotation, which plays an important role in horizontal soil reaction determination, varies from 50% to 20% of the caisson height from the caisson base. Effects of material and interface nonlinearities involving separation, slippage and base uplifting on the caisson foundation response were also taken into account in some of the studies. The soil nonlinearity has been found to reduce the stiffness coefficients by 8.6%. The change in the caisson response under dynamic loading in comparison to statically applied loads has also been summarized in this paper. Present comparative study highlights the necessity of thorough research in design of caisson foundations under both static and seismic loading conditions.

RÉSUMÉ: Plusieurs méthodes analytiques proposées et études de modèle numérique pour simuler les interactions de caisson-sol ont été passées en revue et une étude comparative a été présentée. En littérature éditée, les chercheurs avaient essayé de capturer la distribution d'effort à l'interface de base-sol de caisson qui a montré partager significatif des charges par la base et la circonférence de caisson. La présente étude prouve que la position du point de rotation, qui joue un rôle important dans la détermination horizontale de réaction de sol, varie de 50% à 20% de la taille de caisson de la base de caisson. Des effets des non-linéarités de matériel et d'interface comportant la séparation, le patinage et la base élevant sur la réponse de base de caisson ont été également pris en considération dans certaines des études. La non-linéarité de sol s'est avérée pour réduire les coefficients de rigidité par 8,6%. Le changement de la réponse de caisson sous le chargement dynamique par rapport aux charges statiquement appliquées a été également récapitulé en ce document. L'étude comparative actuelle accentue la nécessité de la recherche complète dans la conception des bases de caisson dans des conditions de charge statiques et séismiques.

KEYWORDS: Caisson foundation, Winkler model, Nonlinear analysis, Seismic analysis.

1 INTRODUCTION

Caisson foundations (also known as well foundations), deeply embedded in soil, provide a solid and massive foundation system for heavy loads. Major structures, especially long bridges spanning over land or water (Gerolymos and Gazetas 2006a) and some high-rise buildings (Katzenbach et al. 2016) use these types of foundations to transfer the loads to soil stratum below. Along with the loads coming from the superstructure and load due to self-weight, caisson foundations are generally subjected to wind forces, forces due to water currents, traction due to braking of vehicles, earth pressure and many more. In the earlier days, caisson foundations with large cross-sectional area and high rigidity were believed to provide a safe foundation system against earthquake induced loading. But this assumption went wrong during the 1995 Kobe earthquake when many structures resting on caisson foundations were found to be nonimmune to seismic loading and suffered severe damage (Gerolymos and Gazetas 2006a, Mondal et al. 2012).

Over the years, several theoretical methods based on different approaches such as bulkhead concept (Terzaghi 1943), elastic theory concept (IRC : 45, 1972), multi-spring Winkler model concept (Gerolymos and Gazetas 2006a,b,c, Tsiggions et al. 2008, Varun et al. 2009) and two-dimensional nonlinear analysis (Mondal and Jain 2008, Mondal et al. 2012) have been proposed to study the static and seismic responses of caisson foundations. In these methods, researchers mostly attempted to capture the stress distribution around the caisson-soil interface which showed significant contribution from both caisson base and circumference towards resistance towards applied load. The soil non-homogeneity along with the separation and slippage at the caisson-soil interface also have been taken care of by some of the methods mentioned above. The intent of this study is to critically review and compare some of the proposed methods in order to investigate the foundation behaviour under static and seismic conditions.

2 THEORETICAL METHODS

2.1 *Static analysis of caisson foundation*

To analyze the response of the caisson foundations under static condition, researchers mainly focused in estimation of allowable bearing pressure and lateral stability analysis. Caisson foundations (except floating caissons) are generally embedded up to a certain depth below the highest scouring level. The portion of the foundation lying below the extreme possible scouring level is assumed to provide lateral stability of the caisson foundation against transverse loads.

2.1.1 *Allowable bearing capacity calculation*

Caissons are embedded in a soil medium due to its own weight and generally are rested on a hard stratum. Although the embedded portion of the foundation under maximum scouring scenario provides the side resistance against lateral loading, the skin friction due to this embedded part is generally ignored in bearing capacity calculation. Teng (1962) suggested that settlement can be a guiding factor of the bearing pressure of well foundations embedded in sand and proposed an equation of bearing pressure for a permissible settlement. According to

Indian design code IS : 3955 (1967), allowable bearing pressure for wells in cohesionless soils can be evaluated from the standard penetration number, *N*. As per this codal provision, the allowable bearing pressure, Q_a (in kN/m^2), for a foundation of width *B* (in m) and depth (below maximum scour level) *D* (in m) can be expressed as:

$$Q_a = 0.054\, N^2 B + 0.16\,(100 + N^2)\, D \qquad (1)$$

2.1.2 *Lateral stability analysis*

For lateral stability analysis, several methods developed using different approaches are available. Terzaghi (1943) proposed a methodology for lateral stability analysis based on a free, rigid bulkhead concept. Later, Pender (1947) established a new approach by assuming the soil around the piers as linear springs with increasing stiffness along depth. IRC : 45 (1972) proposed a guideline to obtain the resistance of soil below the deepest possible scouring depth in the well foundation design. In this proposal, concept of elastic theory has been adapted to check the calculated base pressure. In addition, the ultimate soil resistance has also been computed from earth pressure diagram (Figure 1). This codal provision also discussed about experimentally observed failure patterns of well foundations under ultimate conditions. The location of point of rotation at failure was found to depend on the load from the superstructure which further influences the resistance of the foundation system.

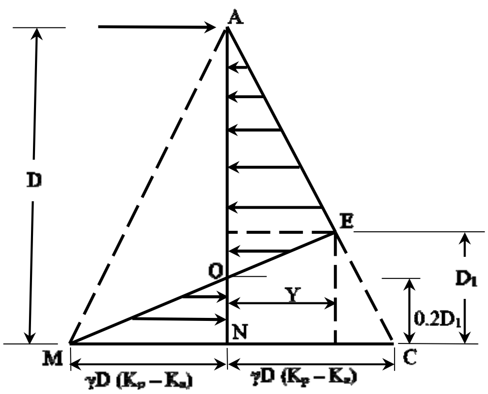

Figure 1. Ultimate soil pressure distribution at the front and rear faces of the well foundation [reproduced after IRC : 45 (1972)]

2 .2 *Seismic analysis of caisson foundation*

Over the past few decades, researchers are developing interest in studying the behaviour of deep foundations under seismic loading condition. However, similar studies on caisson foundation are limited till date. In this section, some of the published works on seismic analysis of caisson foundations have been summarized.

2.2.1 *Analytical methods*

Gerolymos and Gazetas (2006a) developed a generalized multi-spring Winkler model for analysing the behaviour of rigid caisson foundations under lateral loading which are embedded in elastic homogeneous soil (see Figure 2). This four-spring Winkler model incorporates different types of spring: lateral and rocking springs, which are distributed along the caisson height and concentrated shear and rotational springs at the caisson base. The horizontal soil reaction and the moment generated due to vertical shearing of the caisson periphery are taken care of by the distributed horizontal and rocking springs respectively. On the other hand, horizontal traction on the caisson base is captured by the concentrated base translational spring. Along with the springs, dashpots are also attached in parallel to capture the viscous property of soil coming from both radiation damping and hysteresis damping.

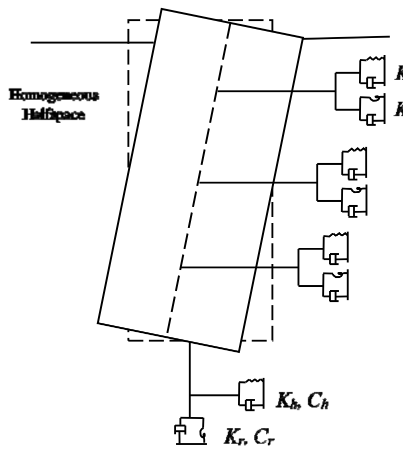

Figure 2. Different types of springs and dashpots (distributed and concentrated) for caisson response analysis [reproduced after Gerolymos and Gazetas, 2006a]

The authors extended the work of linear multi-spring model by taking the soil and interface nonlinear behaviour into account (Gerolymos and Gazetas 2006b). In this study, soil nonlinearity around the caisson foundations were modelled by involving soil nonlinearity, separation and breakdown of the soil-caisson interface bonding, base uplifting, and material softening with large number of cycles. Gerolymos and Gazetas (2006c) further investigated the response of a caisson foundation placed in a nonhomogeneous medium.

Tsiggions et al. (2008) dealt with the seismic response of a bridge pier resting on caisson foundations, embedded in linear soil strata. The superstructure was modelled as a 2DOF system where the mass was concentrated at the pier head and the pier was modelled as beam (see Figure 3). From the analysis, the time period of the overall system was found to depend on slenderness ratio of the foundation.

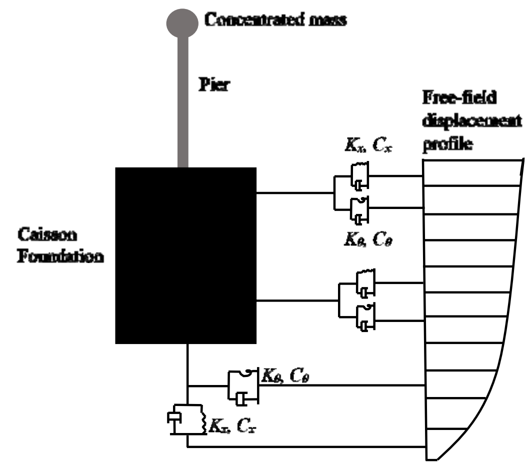

Figure 3. The proposed model with different types of springs and dashpots shaken by the free-field displacement profile [reproduced after Tsiggions et al., 2008]

Varun et al. (2009) analysed caisson foundations for slenderness ratio (*D/B*) of 2-6 under transverse loading by developing a simplified analytical model. For the case of caisson top subjected to lateral loading, the stress resultants acting on the caisson periphery is depicted schematically in

Figure 4. In this analysis, the coupling of the soil layer responses were assumed to be neglected and total response was obtained by integrating the resistances offered by each spring which has been allocated for individual soil layer. Euler beam theory has been adopted for the analysis of embedded foundation response which were subjected to the non-axial loading at the top. Spring functions which rely on frequencies also have been formulated in this study.

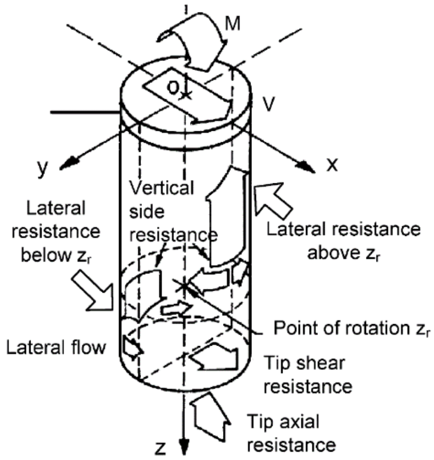

Figure 4. Schematic diagram of normal and shear stress resultants found to be acted on the caisson perimeter and the base due to lateral loading [after Varun et al. 2009]

2.2.2 *Numerical analysis*

Mondal et al. (2012) performed the seismic analysis of a soil-well-pier system by using different approaches. In nonlinear dynamic analysis, multiple yield surface plasticity model was used to characterize the nonlinear hysteric behavior of soil. On the other hand, as a first step of the equivalent linear approach, SHAKE was used to obtain the effective shear modulus and damping ratio values for each soil layer. This is generally done by free-field response analysis of soil for a given ground motion. Disagreement among the response values obtained by these two above mentioned approaches manifested the necessity of the rigorous nonlinear analysis (Mondal and Jain 2010). Later, the authors proposed a 1-D spring-dashpot model along with these two popularly known approaches and estimated their comparative performances (Mondal et al. 2012). For performing seismic analysis, nine different earthquake motions categorized by three scaled PGA values of ranging from 0.2 g, to 0.6 g were considered by the authors. After studying the effectiveness of different types of springs on foundation response, authors finally proposed a 1-D model with three types of spring dashpots.

2.3 *Comparison between the proposed theoretical methods*

In this section, the above mentioned theoretical methods have been critically reviewed and a summary of the foundation responses captured by different methods is presented.

In lateral stability analysis, horizontal soil reactions have been evaluated by different approaches. In this analysis, the point of rotation along the vertical axis also plays a vital role in determination of the maximum horizontal soil reaction. In Fig. 5, the dependency of position of point of rotation (Gerolymos and Gazetas 2006c) on various parameters such as loading magnitude, embedment depth, non-homogeneity of soil etc. has been illustrated. For smaller embedment depth, the point of rotation has been found to be roughly at 50% of the caisson height from the caisson base.

On the other hand, for greater embedment depth, the point of rotation was located at 20% of the caisson height from base which is similar to the codal provision (IRC : 45, 1972).

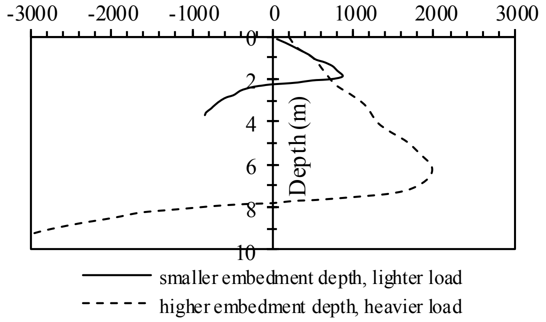

Figure 5. Variation of horizontal soil reactions along depth for two circular caissons embedded in cohesive soil

As per the analytical methods described in this paper (Gerolymos and Gazetas 2006a, Tsiggions et al. 2008), normalized stiffness coefficient values can be expressed in terms of slenderness ratio (*D/B*). Fig 6 represents the difference between the coefficient values for square caisson foundations embedded in homogeneous soil obtained by the two methods. The distributed lateral static spring constant does not vary significantly with slenderness ratio and the values obtained using these two methods are in close agreement. However, the distributed rotational static spring constants suffered a considerable variation along with the slenderness ratio. In this case, Tsigginos et al. (2008) overestimated the normalized rotational spring constants by a range of 52.4% to 23.8%.

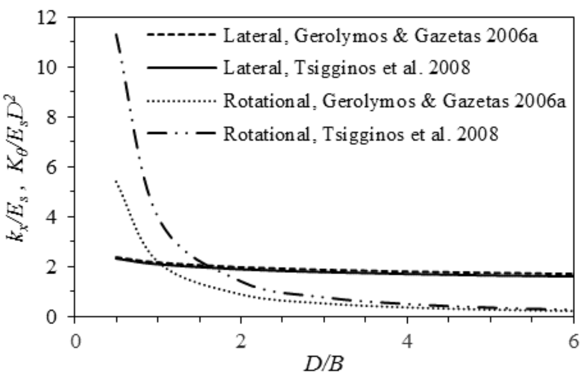

Figure 6. Distributed spring coefficients for a square caisson calculated for different slenderness ratios (*D/B*) under lateral static loading condition

For simplicity purpose and to reduce computational effort, many studies did not consider the soil non-homogeneity in evaluating the foundation behavior under different loading combinations. Fig. 7 depicts the effect of the soil-inelasticity on the normalized lateral spring coefficients used for a circular caisson (Gerolymos and Gazetas 2006a,b). The elastic multi-spring model is found to overestimate the spring coefficients by 8.6%, which actually enhanced the necessity of performing the nonlinear analysis.

Table 1 shows a comparison of the caisson responses (i.e., lateral displacement at top and rotation) under applied static loading and dynamic loading (Gerolymos and Gazetas 2006c). For the case of static loading, responses were obtained for the following cases: a) monotonically applied horizontal load of 5 MN at the caisson top, and b) a combination of horizontal force (= 1.5 MN) and overturning moment (= 15 MN-m) applied at caisson top.

On the other hand, in order to study the dynamic response of caisson foundation, 4 cycles of sinusoidal loading with frequency of 2 Hz and amplitude same as the two cases of static loading were applied. From Table 1, it can be seen that there is considerable difference in response under static and dynamic loading. Dynamic response not only depends on the amplitude of the applied loading, but also on its frequency and duration. Thus, though the amplitudes of the static and dynamic loading were same, lateral displacement and rotation under dynamic conditions may be more or less than that under static conditions (as evident from Table 1). Hence, this study highlights the need for extensive study on dynamic response under various types of applied loading (sinusoidal loading with varying frequency and duration, random earthquake loading).

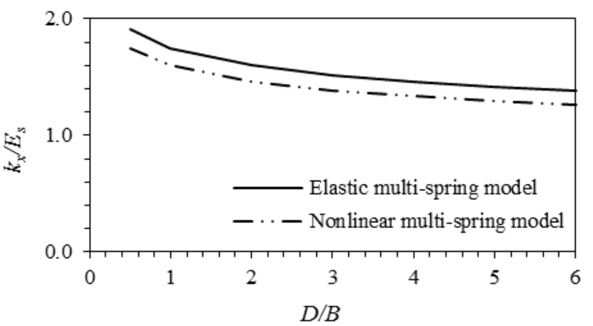

Figure 7. Translational spring coefficients for a circular caisson calculated for different slenderness ratios (*D/B*) under lateral static loading condition

From the comparative study of caisson responses, namely shear force and bending moment estimated by different spring-dashpot models, it can be seen that the spring constants are varying in a considerable manner (sometimes the error is more than 50%) under seismic loading condition (Mondal et al. 2012).

Table 1. A comparison of response of caisson foundations under static and dynamic loading conditions

Loading conditions	Response	Static	Dynamic	% change
5MN horizontal force, applied at the caisson head	Maximum Lateral displacement of caisson	10.64 cm	9.77 cm	8.2
	Maximum Rotation of caisson	0.021 rad	0.02095 rad	-
1.5MN horizontal force & 15 MN-m overturning moment, applied at the caisson head	Maximum Lateral displacement of caisson	8.38 cm	8.66 cm	3.3
	Maximum Rotation of caisson	0.0252 rad	0.0253 rad	-

3 CONCLUSIONS

A comparative study of theoretical methods used to capture the caisson foundation behaviour under static and seismic loading has been presented in this paper. The major findings from the present study are:

1) Various researchers have developed several theoretical methods based on broadly classified soil types. However, rigorous analyses involving wide ranges of soil properties is missing in most of the studies. Also none of the above mentioned methods take care of the liquefaction phenomenon.
2) Based on the study for determining the location of point of rotation, it has been observed that the point of rotation lies between 50% to 20% of caisson height measured from the base. This location is found to be dependent on loading condition, embedment depth and soil non-homogeneity.
3) Present comparative study also shows that consideration of soil inelasticity in Winkler multi-spring model reduces the normalized lateral spring constants by 8.6%.
4) Dependency of normalized stiffness coefficients (both lateral and rotational) on slenderness ratio has also been discussed in this study. The rotational spring constants have been found to vary significantly with slenderness ratio, whereas the variation is not so substantial in the case of lateral spring coefficients. Tsigginos et al. (2008) assumed the soil behavior to be linear and thus overestimated the normalized rotational spring constants by a range of 52.4% to 23.8%.
5) From the comparative study on caisson response under static and dynamic loading (Gerolymos and Gazetas 2006c), it has been seen that dynamic response can be quite different from static response. However, the authors did not consider the effect of varying frequency and number of cycles of applied loading on response. Thus, further research is required to study the effect of various types of dynamic loading on foundation response.

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