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Effects of Torsion on Caisson Capacity in Clay

H A Taiebat
BSc (Hons), MES, PhD
Research Associate, The University of Sydney, Australia
J P Carter
BE, PhD, DEng, FIFAust, MASCE
Challis Professor of Civil Engineering, The University of Sydney, Australia

Summary: This paper presents the results of a numerical study on the effects of torsional loads in reducing the vertical and lateral bearing capacity of caisson foundations. The caisson is assumed to be embedded in a homogeneous soil deforming under undrained conditions. The performance of a typical caisson foundation under axial, torsional and lateral forces is investigated followed by the interaction of torsion with the other two components of loading. The ultimate capacity of the caisson under combined loading is presented in the form of failure envelopes in the axial-torsional and the lateral-torsional loading planes. The results of this study show that generally torsional forces significantly affect the vertical and lateral capacity of caisson foundations. However, their effects on lateral capacity can be ignored in some cases of practical significance, i.e., those where the horizontal line of action of the force applied to the padeye passes within about 0.2 of a diameter of the vertical axis of the cylindrical caisson.

INTRODUCTION

Over the last two decades caisson foundations have been used increasingly in marine environments for temporary or permanent mooring of floating offshore facilities, tension leg platforms as well as gravity based structures. Recently, their use has also been proposed for foundations for offshore wind turbines. They are considered as particularly reliable and cost-effective alternatives to more conventional mooring systems in deep and ultra deep waters. They have advantages over other conventional offshore anchoring systems because of their large bearing capacity and the efficiency of their installation. Caisson foundations have typically a large diameter and a wide range of length-to-diameter ratio, so they provide a relatively large lateral and axial capacity. A caisson can partially penetrate into the soil under its own weight. Further penetration is usually facilitated by pumping water out of the caisson chamber, thus applying suction inside the caisson. The difference between the external and internal fluid pressures acts as an external surcharge pushing the caisson into the soil. This simple installation procedure is probably the greatest advantage of caisson foundations over pile foundations. A suction caisson can be withdrawn later by applying a positive pressure inside the chamber to pull it out of the soil.

In the marine environment caisson foundations are subjected to all types of axial, lateral and torsional loading. Acting as a part of mooring system, a caisson foundation is predominantly subjected to axial and lateral loading, transferred from a mooring line to a padeye on the caisson wall. Any misalignment of the padeye or any change in the direction of the mooring line induces torsional loads to the caisson. Significant torsional loading might also be expected when caissons are used to support tall structures subjected to large eccentrically applied forces, such as modern wind turbines.

The response of caisson foundations to axial and lateral loads has been well studied. However, little is known of the effects of torsional loads on the axial and lateral load capacities of this type of foundation. In general, torsional loads are believed to reduce the resistance of cylindrical foundations subjected to vertical and lateral loading, but this effect has not previously been quantified. The extent of the reduction in the capacity of a caisson subjected to simultaneous torsion and lateral and axial loads is the subjects of this paper. The results of this study have practical applications in the offshore foundation industry. It is demonstrated that installation of caisson foundations may be facilitated if a torsional force is combined with the vertical installation force (or suction). Guidance is also provided for tolerable misalignment of lateral forces applied to caissons via a padeye.

A series of finite element analyses of caisson foundations was performed in order to obtain an insight into the effects of torsional loads on the capacity of foundations subjected to vertical or lateral loads. As the main aim of this study is to find the overall interaction of torsion with the axial and lateral forces, the problem was solved for only one typical caisson with a length-to-diameter ratio of 2. This is within the typical range found in practice.

FINITE ELEMENT MODEL

The caisson foundation considered here has a diameter D and a length L = 2D, embedded in a homogeneous soil that deforms under undrained conditions. The soil is assumed to obey the Tresca failure criterion. It has a uniform undrained shear strength of s_u and an undrained Young's modulus of $E_u = 300\,s_u$. A Poisson's ratio of $\nu \approx 0.5$ (= 0.49) was assumed for the soil to approximate the constant volume response of the soil under undrained conditions. The rigidity index G/s_u is therefore equal to 100, where G is the shear modulus of the soil. The caisson material has a Young's modulus of $E_c = 1{,}000\,E_u$.

The geometry of the problem under investigation is axi-symmetric, but the loading is of course non-symmetric. The axi-symmetric nature of the geometry was exploited to achieve economies in obtaining the finite element solutions. The finite element mesh used in the analyses has 12 wedges of elements in the circumferential direction. Each wedge consists of 304 isoparametric (20 node) brick elements. A thin layer of elements has been used around and under the caisson in order to capture the effects of shearing close to the foundation. A schematic representation of half of the three-dimensional finite element mesh used in the analyses is shown in Figure 1, which also defines the overall geometry of the finite element model.

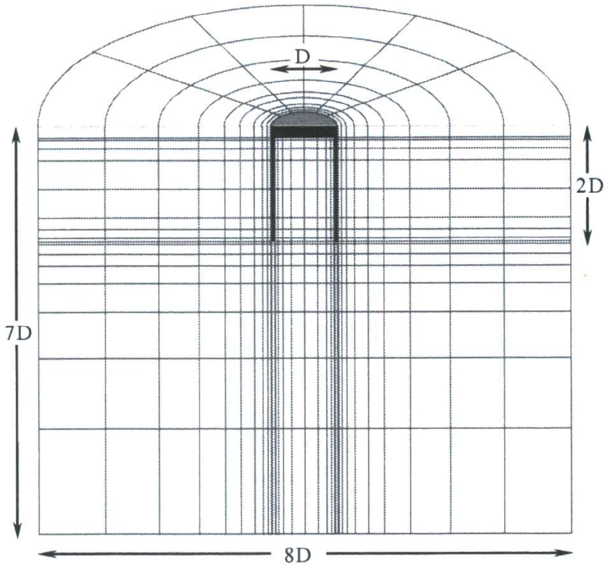

Figure 1: Finite Element Mesh and Geometry of the Problem

The finite element formulation used in the analyses here is based on the "semi-analytical" approach in finite element modelling described by Zienkiewicz and Taylor (1989), which is an efficient tool for three-dimensional analyses. A semi-analytical finite element method, based on representation of nodal variables in terms of discrete Fourier series, has been integrated in the finite element code AFENA (Carter and Balaam, 1995). Application of this method in the analyses of three-dimensional problems has shown a considerable reduction in computational time. Details of the semi-analytical method used in this study may be found in Taiebat and Carter (2001).

Most of the analyses were performed under "displacement-defined" conditions, where a vertical or lateral displacement together with a torsional displacement were applied to the foundation at the ground level. It is assumed that the loads are applied at a rate sufficiently rapid that the surrounding soil deforms under undrained conditions. No provision has been made to model any separation or de-bonding that may occur between the soil and the foundation.

FINITE ELEMENT RESULTS

The resistance of the caisson foundation under each individual component of loading, torsional, axial or lateral loading, is presented first followed by the performance of the foundation under combinations of torsional-axial and torsional-lateral loads.

Torsional Resistance

Assuming the full value of the undrained shear strength of the soil is mobilized as a shear stress at the caisson-soil interface, the theoretical value for the ultimate torsional capacity of caisson foundations, T_u, can be calculated as the sum of the base resistance and the shaft resistance, i.e.,

$$T_u = s_u \pi D^2 \left(\frac{L}{2} + \frac{D}{12} \right). \qquad (1)$$

For the case where L = 2D, the ultimate torsional capacity of the caisson is therefore $T_u = 3.402\,s_u D^3$.

The load deflection curve predicted by a finite element analysis of the caisson under a torsional loading is presented in Figure 2. The response of the caisson under the torsional load is elastic-perfectly-plastic. The torsional resistance increases linearly to its ultimate value at a rotation of about 0.006 radian, after which the resistance remains constant. The ultimate torsional resistance predicted by the finite element analysis is equal to $T_u = 3.396\, s_u D^3$, which is in excellent agreement with the theoretical value given by Equation 1.

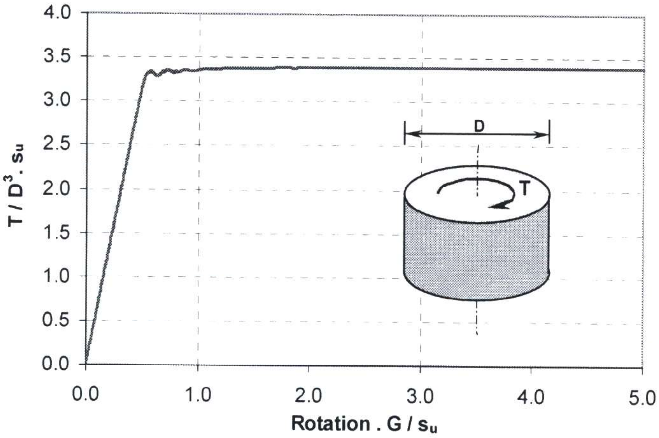

Figure 2: Caisson Response Under Torsional Loading

Axial Resistance

The axial bearing capacity of the caisson foundations in undrained soil, V_u, can be approximated using the conventional method of bearing capacity calculation that is widely used by the geotechnical professions, e.g., from the equation suggested by Vesic (1975), as:

$$V_u = \zeta_s \,.\, \zeta_d \,.\, N_c \,.\, A \,.\, s_u \qquad (2)$$

where A is the plan area of the caisson, N_c is the bearing capacity factor for a strip footing corresponding to the cohesion of the soil, ζ_s and ζ_d are factors that include the effects of the shape of the footing and the effects of embedment of the foundation. The bearing capacity factor for undrained soil is equal to $N_c = (2+\pi)$. The shape factor for circular footing is suggested as $\zeta_s = 1.2$. The embedment factor for a circular footing was suggested as $\zeta_d = 1 + 0.4 \tan^{-1}(L/D)$, for the case of L/D=2, the embedment factor is $\zeta_s = 1.443$. Therefore, for the special case considered here the axial load capacity of a buried circular footing is given by the conventional method as $V_u = 8.9\, A\, s_u$. The effects of the adhesion developed on the caisson wall are not included in this method.

Deng and Carter (1999) recognised the effect of adhesion developed on the wall of the foundation and suggested an equation for the uplift capacity of caisson foundations in an undrained homogeneous soil as:

$$V_u = N_p \,.\, \zeta_s \,.\, \zeta_{ce} \,.A \,.\, s_u \qquad (3)$$

Where $N_p \approx 9.0$ is the uplift capacity factor and $\zeta_{ce} = 1 + 0.4\,(L/D)$. Equation (3) results in an uplift capacity of $V_u = 19.44\, A\, s_u$ for a caisson with L/D=2. It should be noted that the uplift capacity problem of a caisson in soils deforming under undrained conditions is a reverse compressive bearing capacity problem and can be treated similarly (e.g., Anderson *et al*, 1993). Therefore, Equation (3) can equally be used for compressive bearing capacity of caisson foundations. The results of the finite element analysis also do not indicate any significant change in the axial capacity when the direction of loading is reversed.

The results of a finite element analysis of the caisson under axial compression are presented in Figure 3. The response of the caisson is approximately linear at the beginning of loading where about 65% of the ultimate axial resistance is mobilized. After a rapid bend in the load-deflection curve, the rate of increase in the resistance reduces significantly. At a relatively large displacement the increase in the resistance becomes insignificant and the ultimate load is approached. The ultimate axial resistance of the caisson predicted by the finite element analysis is $V_u = 17.53\, A\, s_u$ which is smaller than the value predicted by Equation (3). The ultimate axial load is obtained at a vertical displacement of about 44% of the caisson diameter. A slightly larger axial capacity could have been obtained at a greater vertical displacement of the caisson. The relatively fine finite element mesh adopted in the current study may also have contributed to the lower predicted value of the ultimate axial capacity compared to that suggested by Deng and Carter (1999).

Lateral Resistance

The lateral resistance of caisson foundations in an undrained homogeneous soil can be given as:

$$H_u = N_h \,.\, L \,.\, D \,.\, s_u \qquad (4)$$

where H_u is the ultimate lateral capacity of the caisson and N_h can be defined as the lateral capacity factor. Deng and Carter (1999) suggested a lateral capacity factor that is a function of the point where the load is applied. For lateral load applied at the surface the lateral capacity factor suggested by Deng and Carter is $N_h = 4.8$.

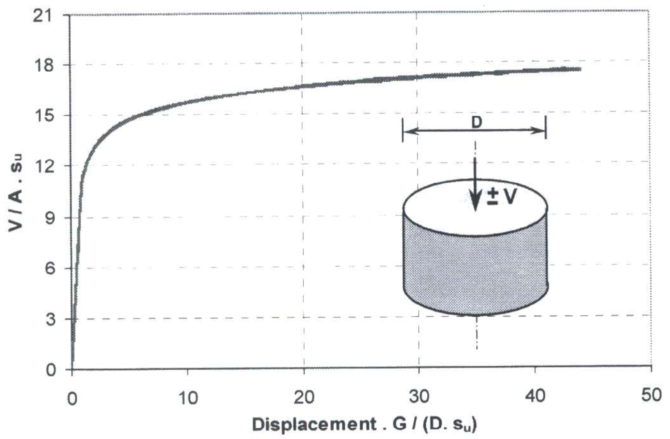

Figure 3: Caisson Response Under Axial Loading

The results of the finite element analysis of the caisson subjected to lateral loading applied at the groundline are presented in Figure 4. A lateral capacity factor of $N_h = 3.92$ is obtained at a relatively large lateral displacement. Again, the lower prediction of the lateral capacity factor may be attributed to the relatively fine finite element mesh adopted in the current study, although this point probably warrants further investigation.

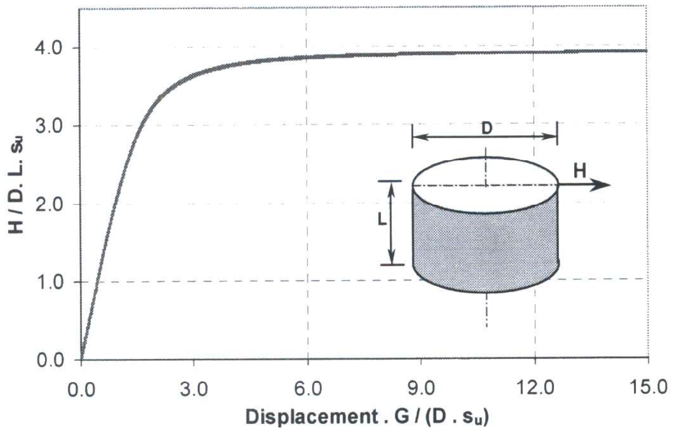

Figure 4: Caisson Response Under Lateral Loading

Resistance Under Combined Axial and Torsional Loading

The response of the caisson foundation under a combination of axial and torsional deformations is presented in Figure 5. For this case it was assumed that the torsional rotation and the axial displacement increased in a fixed ratio. Generally there is a sharp increase in the torsion resistance at the beginning of loading. The torsional resistance decreases and then remains constant at later stages of the loading. The axial load-displacement curve is approximately linear at the beginning of loading where about 2/3 of the axial resistance is mobilized. After that the rate of increase in the axial resistance reduces and eventually becomes insignificant at the point where failure is assumed to occur.

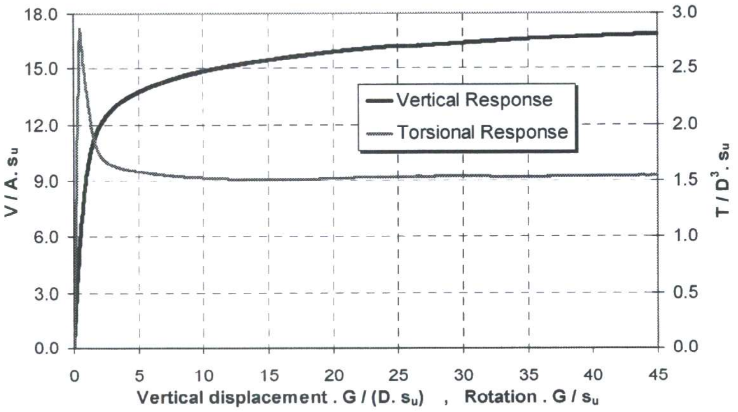

Figure 5: Caisson Response Under a Combination of Axial and Torsional Loading

In order to evaluate the interaction between the axial and torsional loading, a series of finite element analyses was performed using different ratios of the vertical displacement to the rotation of the caisson. The results of the finite element analyses are presented in Figure 6 as a failure locus for the caisson under combinations of axial and torsional forces. In this figure, the axial and torsional forces are normalized with their maximum values, V_{max} and T_{max}, obtained under either pure axial or pure torsional loading. The response of the caisson to the loading for each case is similar to that shown in Figure 5, i.e., the torsional resistance remains constant after a sharp increase at the beginning of the loading while the axial resistance monotonically approaches an ultimate state. For each loading case the ultimate axial capacity is obtained at a vertical displacement generally greater than 40% of the diameter of the caisson. It is noted that these are small strain results and in reality the ultimate axial capacity may increase slightly at larger vertical displacements.

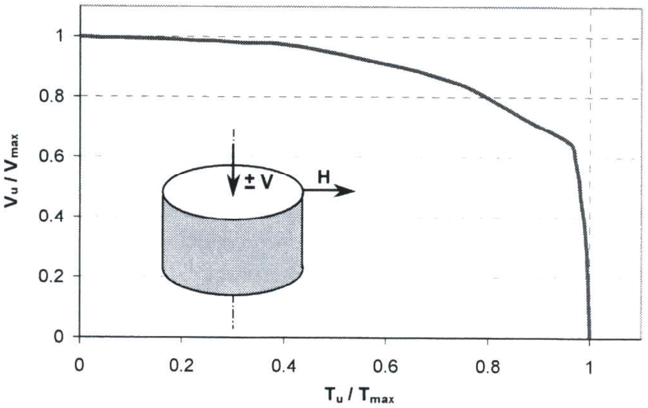

Figure 6: Failure Locus in the Vertical-Torsional Loading Plane

The failure locus presented in Figure 6 shows that torsional forces have a large effect on the axial bearing capacity of the caisson foundation. When much of the shearing strength around and under the caisson is mobilized by torsion, the axial capacity of the foundation reduces significantly. For axial loads lower than about 0.6 V_{max}, torsional displacements govern the failure mechanism of the caisson foundation.

The ultimate axial capacity of the caisson is shown in Figure 7 in terms of the inclination angle of the load applied at the outer boundary of the caisson. The inclination of a pair of loads to the vertical induces rotation of the caisson while the net lateral force is zero. The inclination angle can be calculated as: $\alpha = \tan^{-1}(2T/DV)$. Inclination angles less than 10° do not have a significant effect on the axial resistance of the foundation. However, at a larger inclination angles the effects become very significant. An inclination angle of $\alpha = 45°$ reduces the axial capacity of the caisson to half of its maximum value.

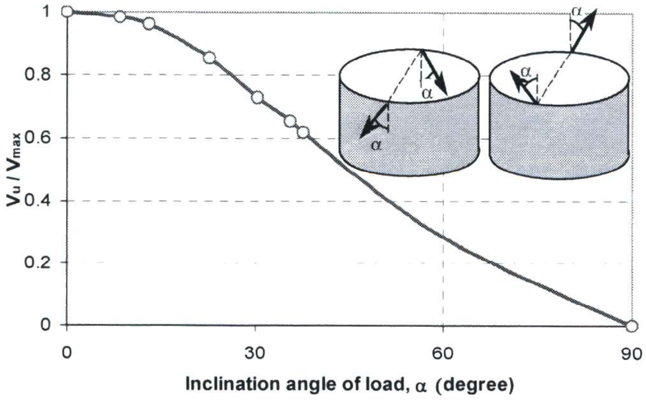

Figure 7: Effects of Load Inclination on the Ultimate Axial Capacity

Resistance Under Combined Lateral and Torsional Loading

The response of the caisson foundation to different combinations of lateral and torsional deformations is presented in Figure 8 as a failure locus in the lateral-torsional loading plane. The ultimate lateral and torsional forces are normalized with their maximum values, H_{max} and T_{max}, which can be obtained under pure lateral and pure torsional loading, respectively. For each case, the ultimate lateral capacity is obtained at a horizontal displacement generally greater than 10% of the diameter of the caisson where the lateral resistance has reached a constant value. Figure 8 shows that as the torsional force increases to its maximum value, the lateral resistance of the foundation decreases to about 60% of its maximum value. For the lateral loads lower than about 0.6 H_{max}, torsional displacements govern the failure mechanism of the caisson foundation.

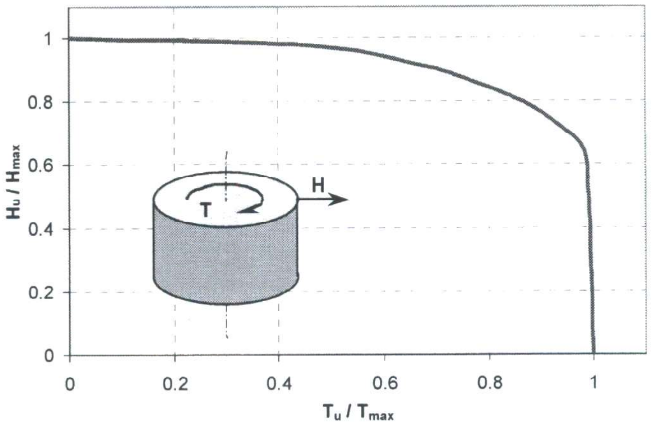

Figure 8: Failure Locus in lateral-Torsional Loading Plane

The effects of the misalignment of the padeye on the ultimate lateral capacity of the caisson are shown in Figure 9. Misalignment in this case is due to the line of action of the applied lateral force not passing through the vertical axis of the cylindrical caisson. The maximum reduction in the ultimate lateral capacity is about 23%, which occurs at a padeye misalignment of $\beta = 90^{\circ}$. For a practical padeye misalignment range, which is normally below 25°, the reduction in the lateral capacity is less than 3% and for practical purposes the effects of torsion on the ultimate lateral capacity can effectively be ignored. In other words, if the horizontal line of action of the lateral forces passes within about 0.2 diameters of the vertical axis of the cylindrical caisson, then such misalignment can effectively be ignored.

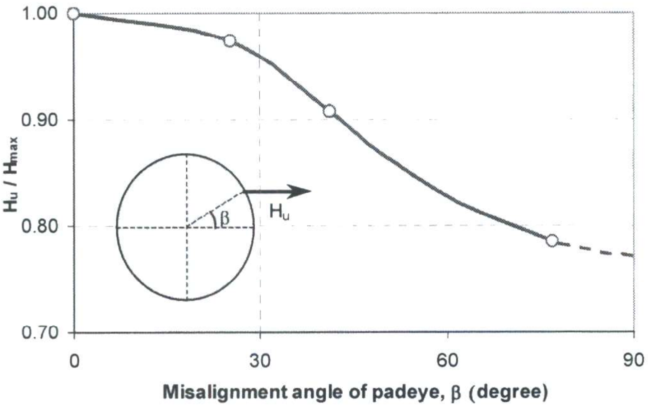

Figure 9: Effects of the Misalignment of Padeye on the Lateral Capacity

CONCLUSIONS

This paper has presented the results of a numerical study on the effects of torsional forces on the axial and lateral resistance of a caisson foundation in a homogeneous soil which deforms under undrained conditions. It was shown that generally the torsional strength mobilises at a faster rate compared with the lateral or axial strength of the caisson. In addition, the torsional loads significantly reduce the ultimate axial and lateral capacity of the foundation.

An inclination angle of 45° for the axial load reduces the axial capacity to about half of its maximum value. This has a practical implication for installation or withdrawal of the caisson foundation. Application of a torsional load can be used to reduce the risk of instability of the soil that may occur under large suctions normally required during the installation stage. Torsional loads can also facilitate the withdrawal of the foundation as they should reduce the active pressure required inside the caisson chamber.

The reductions in the lateral capacity at padeye misalignments of 90° (maximum) and 25° are 23% and 3%, respectively. The effects of torsional loads on the lateral capacity of the caisson can therefore be ignored if the torsional loads are applied to the caisson with padeye misalignments of 25° or less.

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