Applied Ocean Research 59 (2016) 129–137

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Evaluation of undrained failure envelopes of caisson foundations under combined loading

Moura Mehravar[a,*], Ouahid Harireche[b], Asaad Faramarzi[c]

[a] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire LE11 3TU, United Kingdom
[b] Department of Civil Engineering, Faculty of Engineering, Islamic University in Madinah, Kingdom of Saudi Arabia
[c] School of Engineering, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 3 February 2016
Accepted 4 May 2016

Keywords:
Bearing capacity
Caisson
Shallow foundation
Three-dimensional finite element modelling
Undrained analysis

ABSTRACT

In this paper, results of a three-dimensional finite element study addressing the effect of embedment ratio (L/D) of caisson foundations on the undrained bearing capacity under uniaxial and combined loadings are discussed. The undrained response of caisson foundations under uniaxial vertical (*V*), horizontal (*H*) and moment (*M*) loading are investigated. A series of equations are proposed to predict the ultimate vertical, moment and maximum horizontal bearing capacity factors. The undrained response of caisson foundations under combined *V*-*H* and *V*-*M* load space is studied and presented using failure envelopes generated with side-swipe method. The kinematic mechanism accompanying failure under uniaxial loading is addressed and presented for different embedment ratios. Predictions of the uniaxial bearing capacities are compared with other models and it is confirmed that the proposed equations appropriately describe the capacity of caisson foundations under uniaxial vertical, horizontal and moment loading in homogenous undrained soils. The results of this paper can be used as a basis for standard design codes of off-shore skirted shallow foundations which will be the first of its kind.

1. Introduction

A suction caisson consists of a thin-walled upturned 'bucket' of cylindrical shape made from steel. This type of foundation has proven to be efficient and versatile as a support for offshore structures and appears to be a very attractive option for future use in offshore wind turbines [1–4]. The thin caisson wall facilitates installation when a pressure differential is induced by suction on the caisson lid, which pushes the caisson to penetrate into the seabed. This is achieved by pumping out the water trapped in the caisson cavity after initial penetration under self-weight [5–8]. The skirt can improve the foundation bearing capacity by trapping the soil between them during undrained loading [9,10]. A number of studies have been conducted on the investigation of bearing capacities of caisson foundations. However, in the most of the former studies the foundation was either analysed as a skirted strip foundation using finite element analyses (FEA) and upper bound solutions or as a surface circular foundation using three-dimensional FEA without considering the skirt length in the simulation [11–20]. On the other hand, offshore foundations are three-dimensional and embedded. The skirt length has a considerable impact on their bearing capacities. Only few studies were performed by considering the caisson foundation using three-dimensional model. Most of these analyses did not comprehensively covered a wide range of practical embedment ratios or investigate all vertical, horizontal and moment bearing capacities [21,22]. A summary of previous studies on undrained bearing capacities and failure envelopes of shallow foundations are presented in Table 1.

In the present study the main objective is to perform three-dimensional (3D) undrained numerical simulations to predict the bearing capacity of caisson foundations under uniaxial and combined loading conditions. The present study refers mainly to the work done by Gourvernec [18], Bransby and Randolph [11], which are essentially plane strain analyses. It has been justified that within such context, the assumption of full bonding between the caisson and surrounding soil is plausible (especially that suction development at the interface in undrained condition prevents separation). Hence, the work performed in the current paper has been limited to a similar context, taking advantage of efficient numerical computations and reasonable computational time. An extension of the present work by implementing interfaces would shed more light on the accuracy of both plane strain and 3D models, but such an extension is beyond the scope of the present paper.

* Corresponding author.
E-mail addresses: M.Mehravar@lboro.ac.uk (M. Mehravar), O.Harireche@gmail.ac.uk (O. Harireche), A.Faramarzi@bham.ac.uk (A. Faramarzi).

http://dx.doi.org/10.1016/j.apor.2016.05.001
0141-1187/

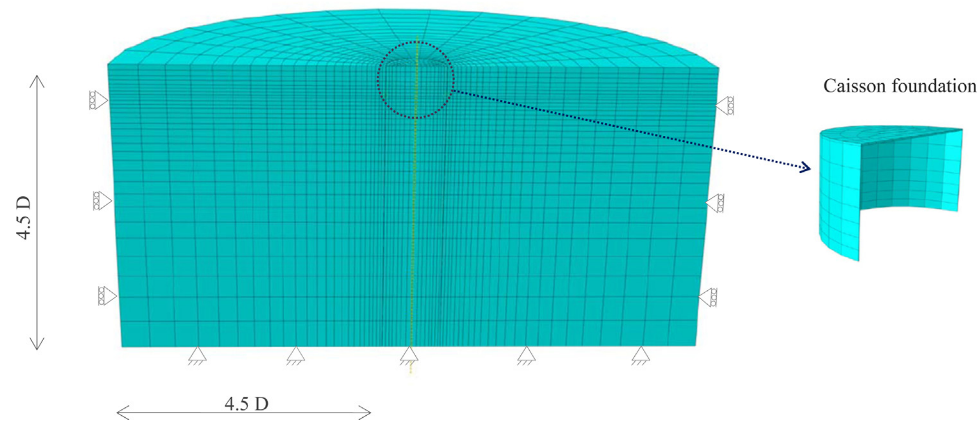

Fig. 1. Finite element mesh and boundary conditions.

Table 1
A summary of studies on undrained bearing capacities of shallow foundation.

Footing Geometry	Embedment		Investigated capacity	Method	Reference
	Surface	Embedded			
Strip	√	–	*VHM*	FEM	[10]
Strip	–	√	*VHM*	FEM/UB	[11]
Strip, Circular	√	–	*VHM*	FEM	[14]
Circular	√	–	*VHM*	LUB	[15]
Circular	√	–	*VHM*	FEM	[16]
Strip	√	√	*V*	FEM/UB	[17]
Strip	√	√	*VHM*	FEM	[18]
Strip	–	√	*HM*	FEM/UB	[13]
Circular	√	–	*VHM*	FEM	[21]
Circular	√	(L/D ≤ 1)	*VH*	FEM	[21]
Circular	√	(L/D ≤ 0.5)	*VHM*	FEM	[22]
Circular	√	(0 ≤ L/D ≤ 1)	*VHM*	FEM	This study

In this paper, a series of three-dimensional finite element analyses using ABAQUS [23] are performed to investigate the effect of the embedment depth on the bearing capacity of shallow foundations in homogenous undrained soil. Different aspect ratios of caisson foundation "L/D = 0, 0.25, 0.5, 0.75, 1", where L is the embedment length and D is the caisson diameter are considered. Uniaxial vertical (V), horizontal (H) and moment (M) bearing capacities are investigated and presented as a series of equations to estimate the uniaxial ultimate vertical, moment and maximum horizontal bearing capacity factors of caisson foundations. Finally, the capacities of caisson foundations under combined VH, VM load space are studied and expressed by failure envelopes.

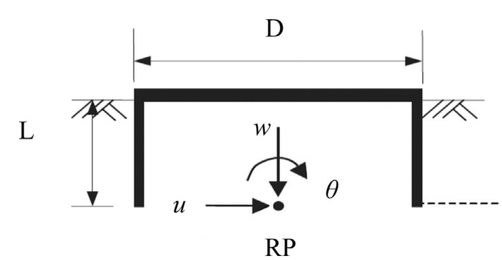

Fig. 2. Foundation geometry.

2. Numerical modelling

2.1. Model geometry and mesh

In order to obtain precise results, a series of three-dimensional finite element analyses were carried out for the practical range of embedment ratios, L/D = 0 (surface foundation), 0.25, 0.5, 0.75 and 1 in a homogenous undrained soil profile. It is important to cover a wide range of values starting from the special case of a surface foundation and moving towards moderately deep foundations (L/D ≤ 1). However, the number of aspect ratio investigated has been kept to a reasonable maximum to keep the simulation concise and comprehensive.

Taking advantage of the symmetrical nature of the problem, only half of the entire system was modelled. Fig. 1 shows a semi-cylindrical section through a diametrical plane of a caisson foundation with L/D = 0.5. This figure also represents the typical finite element mesh for caisson foundation, used in this study. A number of different mesh densities in which element sizes around the caisson wall and tip are considerably refined were performed to obtain accurate results in a reasonable computational time. The mesh is extended 5D from the caisson foundation centre line and top of the soil, respectively so that the failure loads are not sensitive by their position or to the boundary conditions. The caisson thickness is considered 4×10^{-3} D, which reflects a reasonable value for typical caisson foundations. Displacements in all three coordinate directions (x, y and z) at the bottom of the base of the mesh were completely fixed, and also normal displacements on the lateral boundaries were prevented.

The caisson foundation nomenclature and the sign convention which is adopted in this study are presented in Fig. 2.

In order to model the soil, first-order, eight-node linear brick, reduced integration continuum with hybrid formulation element (C3D8RH) is employed. The hybrid elements are appropriate to model the behaviour of near-incompressible materials such as undrained soils [18].