Applied Ocean Research 32 (2010) 414–424

Contents lists available at ScienceDirect

Applied Ocean Research

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

Model testing of suction caissons in clay subjected to vertical loading

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ARTICLE INFO

Article history:
Received 7 May 2010
Received in revised form
25 August 2010
Accepted 7 September 2010
Available online 2 October 2010

Keywords:
Foundations
Vertical loading
Clay
Cyclic loading
Offshore engineering
Suction caissons
Model testing
Geotechnical engineering

ABSTRACT

A wide range of new offshore applications are emerging in the energy sector. The oil and gas industry is targeting minimum facility applications, whilst the renewable energy sector is developing offshore wind turbines, as well as a number of wave and tidal energy devices. The design and installation of the foundations are key considerations in the financial viability of such offshore engineering projects. Suction caisson foundations are a potential solution for these new developments, but design guidance is relatively sparse. This paper considers the vertical loading response of a caisson foundation in clay, during installation and under both monotonic and cyclic vertical loading. The main contribution is the presentation and interpretation of high quality experimental data. Vertical loading is critical for the design of a multi-footing structure of the type that might be used for large offshore wind turbines. We first consider the installation behaviour and compare data from pushed installations and a suction installation with results from a theoretical calculation. We then consider cyclic vertical loading tests, focussing on cyclic amplitudes that take the foundation into tension. Detailed displacement data and pore pressure data are presented.

1. Introduction

With the diminishing supply of fossil fuels, it is likely that energy companies will seek to exploit marginal oil reserves, whilst governments will encourage further deployment of offshore renewable energy devices. There is some overlap in the design of these structures. It is likely that multi-footing structures will be required, in which case the weight is low but the horizontal loads applied, by comparison, are high. This leads to relatively large overturning moments which must be countered by vertical reactions at the foundations. Typical (very approximate) loads for a 3.5 MW offshore wind turbine would be a weight of 6 MN and horizontal load of 4 MN applied at 30 m from the seabed. By spacing the foundations apart, the 120 MNm base moment can be resisted by compression and tension in the foundations. The key design issue is therefore how much tension is permissible for a single loading event, and how far apart the foundations must therefore be spaced. Of course the loading on the structure from the waves and wind is cyclic in nature, and so the load on the foundation will be cyclic. The issue of how much tension can be applied under serviceability conditions is therefore also critical to the spacing of the foundations. It is important to understand the effects of low levels of cyclic tension applied to the foundation, and whether this leads to degradation of the foundation response. It is thought that for foundations on clay the extreme tension can be safely resisted, provided that it does not exceed the undrained capacity of the foundation. However, long term cyclic loading into tension, exceeding the drained friction, may well cause unacceptable displacements. For skirted foundations on sand Byrne and Houlsby [1] and Kelly et al. [2] recommend that tension should be limited to the drained skirt friction, and preferably should be avoided altogether. For multi-footing structures there is also an issue of interactions between the foundations; however, for the purposes of this study we assume that these can be neglected.

The response of suction caissons in clay has been studied more than caisson response in sands. Most research has concentrated on the anchor application, where long but thin suction installed piles are used as anchors for floating facilities. The dominant loading is horizontal, with some tension, although this depends on the nature of the mooring. Some experimental work carried out has explored the effect of cycling about high negative mean vertical loads (cyclic pullout). Relevant information can be found in [3–9]. There has been relatively little research on the use of suction caissons as foundations rather than as anchors. The principal difference is the skirt length-to-diameter ratio as well as the nature of the applied loading. For foundations the skirt length-to-diameter ratio is about one, and the loading consists of vertical and horizontal loads as well as moments.

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0141-1187/$ – see front matter
doi:10.1016/j.apor.2010.09.002

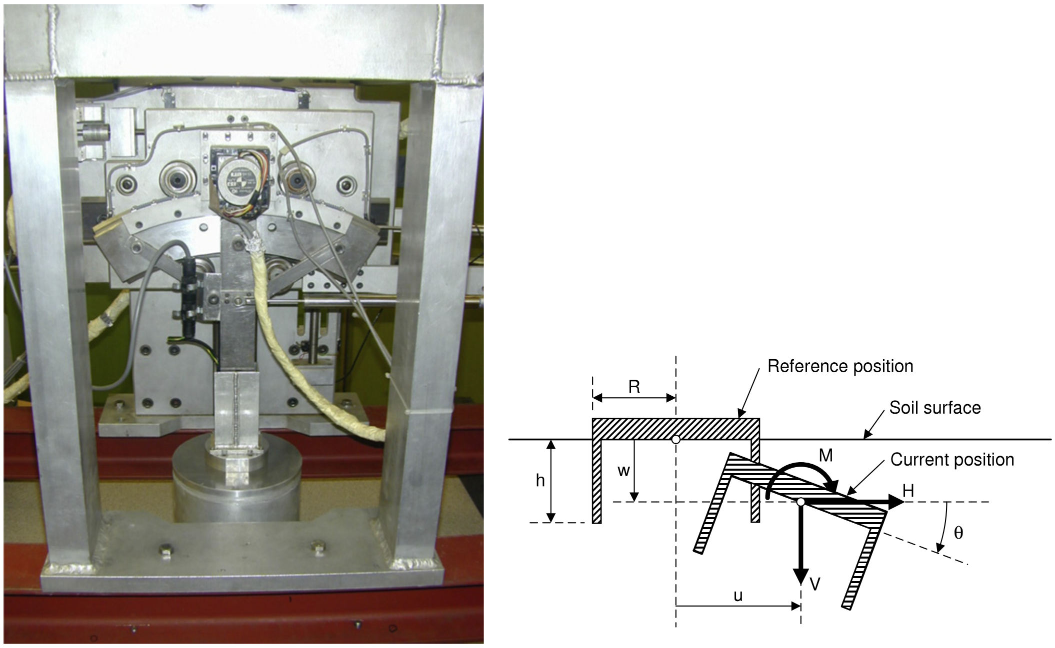

Fig. 1. (a) Three-degrees-of-freedom loading rig at Oxford University and (b) the sign convention for loads from [17] showing positive loads and displacements.

Table 1
Representative Speswhite kaolin clay properties (after de Santa Maria [14] and Martin [15]).

Property	Value
Specific gravity, G_s	2.61
Average effective unit weight, γ'	6.85 kN/m^3
Average moisture, w	50%
Liquid limit, LL	65%
Plastic limit, PL	34%
Coefficient of permeability, k ($p' = 200$ kPa)	$3\cdot10^{-9}$ m/s
Coefficient of consolidation, c_v ($p' = 200$ kPa)	0.3 mm^2/s

There has been recent motivation for exploring caisson foundation response in clay, driven by potential demand as foundations for offshore wind turbines as well as other offshore applications, such as foundations for small sub-sea developments. Previous work on this problem has been carried out by Byrne and Cassidy [10] and Cassidy et al. [11] who explored caisson response in normally consolidated clay on the drum centrifuge at the University of Western Australia. Further work has been carried out by the University of Oxford at field scale, reported by Houlsby et al. [12], and at laboratory scale, reported by Kelly et al. [13]. These latter two papers are important because they demonstrate the scalability of results for tests on clay from the laboratory scale to the field scale and are very relevant for the interpretation of the data presented below. This paper extends the experimental data base by presenting caisson foundation tests in overconsolidated kaolin clay, which is relevant to sites around the UK coastline that consist of hard or stiff clay. The paper reports results from installation tests as well as the displacement behaviour under a wide range of loading conditions including cyclic tensile loading, all of which are relevant to the offshore wind application.

2. Experimental techniques

The testing was carried out on overconsolidated Speswhite kaolin clay, and properties of the clay are given in Table 1. This material was used because its high permeability allows rapid consolidation of large specimens from reconstituted slurry. It has been used in numerous previous studies at Oxford University, and at other institutions, and so is very well characterised [14,15]. A homogeneous kaolin slurry was obtained by mixing water with kaolin at a moisture content of 120% in a ribbon blade mixer. A vacuum pump attached to the mixer was used to de-air the slurry during mixing. The slurry was pumped into cylindrical tanks of 450 mm diameter and 900 mm height. Filter material (vyon) was placed at the top and the bottom of the specimens, allowing drainage to atmospheric pressure during consolidation. The slurry was consolidated to a maximum pressure of 200 kPa. The tests were carried out in the days following the complete unloading of the specimen. To provide a second testing site the specimen was inverted. The strength of the clay was estimated by using a shear vane at depths of 25 and 125 mm. For one of the test samples (FV7_1S) the strength estimates were updated using a fitting of strength profiles from the other tests, combined with a back analysis of the installation and loading data (see [16] for further details). The sample properties are presented in Table 2. To allow further interpretation in this paper we provide an estimate of the strength at the surface of the specimen (s_{u0}) and the rate of strength increase with depth (ρ), assuming that the strength can be fitted simply by a linear profile. This is in contrast to the more complex fitting provided by Villalobos [16]. Despite the consistent preparation procedure, the strength of the clays varied significantly. All normalisations presented in this paper use the undrained strength value measured at the reference depth of 125 mm.

The tests were carried out by using a complex computer-controlled loading rig, shown in Fig. 1(a), which was designed by Martin [15] and modified by Byrne [18]. The rig is capable of applying independently controlled displacement or load paths for each of the three degrees of freedom (vertical, horizontal and rotation) to the foundation. The software allows the application of both monotonic and cyclic loading. The caissons were first loaded vertically, and feedback control was used to keep the horizontal load and moments on the foundation to negligible values. Installation by suction assistance was performed with a vacuum pump connected to a regulating system, so that the suction could be controlled. For the cyclic loading tests it was possible to follow a detailed time history of loading. The loads and displacements are measured at the foundation level and are specified according to the sign convention set out by Butterfield et al. [17] and shown in Fig. 1(b).