

## Response of skirted foundations for buoyant facilities subjected to cyclic uplift loading

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### ABSTRACT

This paper presents results of beam centrifuge tests carried out with an instrumented shallow skirted foundation in lightly overconsolidated soft clay. The effect of one-way and two-way concentric cyclic loading on the load-displacement response during cyclic loading and on the subsequent transient and sustained uplift resistance of the foundation-soil system is considered. The results show that residual uplift displacements and a reduction in average stiffness occurred as the magnitude of the cyclic load and the number of cycles increased, but that undrained and sustained monotonic uplift capacity were enhanced by a preceding sequence of cyclic loading.

**KEY WORDS:** Skirted foundation; clay; centrifuge tests; cyclic loading; uplift.

### NOMENCLATURE

- $q$ : Average vertical stress under foundation
- $v_u$ : Ultimate undrained uplift capacity (expressed as a stress)
- $w$ : Uplift displacement
- $\Delta\sigma$ : Magnitude of change in vertical stress during cyclic loading
- $\sigma_i$ : Minimum required installation stress
- $\sigma_c$ : Applied stress level during periods of consolidation

### INTRODUCTION

Skirted foundations are used to support a variety of offshore structures. The capacity of skirted foundations to resist uplift loading, due to negative excess pore pressure developed within the soil plug, makes them particularly convenient for buoyant facilities. Skirted foundations are favored over conventional pile foundations due to economic benefits arising from simpler construction methods and lower installation cost. A particular application, prompted by the growing worldwide market for liquefied natural gas (LNG), is a new concept to use shallowly embedded skirted foundations to support offshore gravity based LNG terminals. The conceptual design is for these terminals to be buoyant after offloading and impart a sustained uplift load on the foundation that may last for a period of days or weeks. Cycles of offloading and refilling would be considered normal during the

operation of the LNG terminals.

Previous centrifuge testing has been used to study the effect of vertical cyclic loading on skirted and caisson foundations in clay with skirt depth to diameter ratios of  $d/D = 0.5$  (Watson and Randolph 2006) and  $d/D = 4.5$  (Chen and Randolph 2007), and spudcan foundations in sand (Ng and Lee 2002). Small scale model tests have also been used to study the response of bucket foundations (Bye et al. 1995) and suction caissons (Byrne and Housby 2004) in sand subjected to cyclic loading. The effect of lateral cyclic loading on offshore foundations has also been considered (e.g. Watson and Randolph (2006)).

A comprehensive research program involving centrifuge testing and numerical modeling is in progress at the Centre for Offshore Foundation Systems (COFS) to investigate the response of shallowly embedded skirted foundations under transient and sustained uplift loading. An overview of the project is presented in Gourvenec et al. (2007a). The response of a shallowly embedded skirted foundation ( $d/D = 0.3$ ) to cycles of unloading and reloading and the effect of cyclic loading on subsequent transient and sustained uplift resistance is considered in the present paper.

### CENTRIFUGE MODELING

The tests were carried out at the beam centrifuge facility at the University of Western Australia (Randolph et al. 1991). A swinging platform at a radius of 1.8 m provides a nominal working radius of 1.55 m and rated at 40 g-tonnes, this equates to a maximum payload of 200 kg at an acceleration of 200 g.

### Foundation model

The skirted foundation model used in the centrifuge tests is 120 mm in diameter, with skirts 41 mm high and is equipped with an internal cruciform stiffener. The base plate has a thickness of 5 mm, resulting in a maximum potential skirt embedment of 36 mm. The base plate was machined from aluminium and the skirts and stiffeners from stainless steel in order to minimise the foundation weight while ensuring sufficient stiffness of the skirt and stiffener. Tests were performed at an acceleration level of 167g representing a prototype foundation with a diameter  $D = 20$  m and skirt depth  $d = 6$  m ( $d/D = 0.3$ ).