Application of the NGI-Procedure for Design of Bucket Foundations for Offshore Wind Turbines

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ABSTRACT
The offshore wind industry has in recent years showed an interest for using suction buckets for foundations of Offshore Wind Turbines (OWT). Bucket foundations can be used both with monopod support structures and multi-leg support structures as an alternative to monopiles, gravity based foundations and piles. This paper discusses whether the experience from design of foundations for oil and gas structures and the general procedure considering cyclic loading of soils are applicable to bucket foundations for OWTs. The general framework based on the stress path method and the accumulation procedure have earlier shown to be applicable for different foundation problems. The procedure has been verified in model and field tests and some of them are relevant for OWT conditions. Tests and findings from research outside NGI focusing on buckets foundations for OWT are discussed in light of the NGI-procedure. The paper explain why some of the recommendations in literature regarding tension loading of buckets are too conservative. Uncertainties and shortcomings in the procedure are discussed with respect to conditions relevant for OWTs.

KEY WORDS: Offshore Wind Turbines, Bucket foundation, Skirted Caissons, Offshore foundation, Cyclic loading, Tension loading.

INTRODUCTION

OWT Foundations
Monopiles, gravity based foundations and jackets with piles have until recently been the preferred solution for OWT foundations. More than two-thirds of all OWTs installed in Europe are founded on monopiles (EWEA, 2014). However, to reduce installation costs and to handle tougher and harsher load regimes from deeper water and larger turbine loads, there has been increasing interest for alternative foundation methods such as bucket foundations. The foundation concept has been suggested for OWTs by many, e.g. Houlsby et al. (2000).

Bucket foundations

General
Bucket foundation is one of several terms describing the same foundation principle. Suction bucket, suction anchor, skirted caisson, suction caisson and skirted foundations have all in common that they are shaped as one or several cylinders closed at the top, with the vertical walls or skirts penetrated into the seabed. The installation is carried out by applying underpressure inside the bucket. The underpressure implies a downward force and creates favorable pore pressure gradients in permeable soils, reducing the effective stresses and thus the skirt tip resistance and inside friction. The installation process is carried out with low noise emission, it is relatively quick and it requires relatively small ship/barges. After installation, a bucket foundation behaves roughly as an embedded gravity based foundation.

Bucket foundations have been installed all over the world as foundations for oil and gas structures. NGI has been involved in the development of skirted foundations since the beginning of the 1970s when the concept started to be considered for large gravity based concrete platforms (GBS). The experience from this activity is relevant for the wind industry.

Historical review
The first large scale application of suction buckets known by the authors is from Kobe in Japan, where large prestressed concrete cells, 15.5 m in diameter, were penetrated into the clay by underpressure (Sato, 1965). A number of large offshore gravity based platforms equipped with skirts were installed in the North Sea from 1975 (e.g. Eide and Andersen, 1984). The skirts were shallow but introduced some of the same geotechnical problems as bucket foundations. The concept took a great leap forward with the Gullfaks test in 1986 (Tjelta et al., 1986). This large scale penetration test was performed in the Gullfaks field in the North Sea at 200 m water depth. The test model was made up of two 23 m high steel cylinders, each with a diameter of 6.5 m. The successfully performed tests proved the feasibility of penetrating skirts in layered soils by dead weight and suction, and opened up for the skirted caisson foundation on the Gullfaks C platform. Several gravity based concrete platforms with deep-skirted caisson foundations followed Gullfaks C the next 10 years. The largest of them all, the 472 m high Troll A GBS has concrete skirts penetrated 36 m into soft clay (Hansen et al., 1992).

Bucket foundations have been extensively used as suction anchors for floating platforms. The "Gorm anchors" installed in North Sea in 1981 (Senpere. and Auvergne, 1982) was the first example of this...