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Numerical buckling analysis of large suction caissons for wind turbines on deep water

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ABSTRACT

Using large suction caissons for offshore wind turbines is an upcoming cost-effective technology also referred to as bucket foundations. During operation, the monopod bucket foundation is loaded by a large overturning moment from the wind turbine and the wave loads. However, during installation the suction caisson is loaded by external pressure (internal suction) due to evacuation of water inside the bucket and vertical forces due to gravity. The risk of structural buckling during installation of large-diameter suction caissons is addressed using numerical methods. Initial imperfect geometries are introduced, based on the buckling mode shapes from a linear eigenvalue buckling analysis. Different imperfect geometries are introduced to reveal how sensitive the buckling load is to these imperfections. Including the first 21 mode shapes as imperfect geometries will reduce the buckling pressure compared to only considering mode 1. The results of the finite element analysis are compared with current standards for evaluating buckling loads.

1. Introduction

Wind power currently offers a very competitive source of renewable energy, and therefore the market for offshore wind farms is projected to expand rapidly within the next decade. The expenses related to foundations installed on shallow water constitute about one third of the total cost of an offshore wind farm. For wind turbines located on deeper water, the cost of the foundations may be as high as 50% of the total cost. Thus, a new technology is needed to reduce the total cost of offshore wind turbines. This technology could be the bucket foundation. In Fig. 1, four different foundation concepts for offshore wind turbines are shown.

The bucket foundation is an upcoming technology for offshore wind turbines [2]. It is a large cylindrical monopod foundation constructed as a thin steel shell structure. The overall geometry of the bucket foundation can be described by the diameter D, skirt length L and the skirt thickness t, as shown in Fig. 2. Also shown in Fig. 2 is the penetration depth h and the bucket radius R. The concept is similar to the well-proven suction anchor or suction caisson. But the mode of operation of a bucket foundation is very different from that of a suction caisson. The suction caisson is loaded mainly by axial forces. However, the loads from the wind on the wind turbine and the wave loads result in a large overturning moment on the bucket foundation. The loads on the monopod bucket are accommodated by a combination of earth pressures on the bucket skirt and the vertical bearing capacity of the bucket.

The bucket foundation is installed by a combination of suction and water injection at the skirt tip. The applied suction introduces a pressure differential across the lid, effectively increasing the downward force on the bucket lid, as shown in Fig. 3. At the same time, the seepage reduces the skirt tip resistance. This installation technique does not require heavy installation equipment. Furthermore, when the wind turbine is to be removed, the bucket foundation can be removed fairly easily by applying pressure instead of suction.

During installation, the bucket skirt becomes partly embedded, and the degree of skirt fixation increases due to the lateral restraint offered by the surrounding soil. The lateral restraints provided by the soil to the embedded skirt may increase the buckling loads significantly. In the initial installation phase, the free height of the skirt above the seabed is large, and a low suction pressure is needed. For subsequent installation phases, a larger pressure is required.

In deeper waters, the diameter of the bucket must be increased in order to accommodate the larger forces on the foundation. This leads to a larger aspect ratio between the skirt diameter and the wall thickness. The combination of a thin shell structure and suction forces can cause instability in the form of buckling.

A crucial buckling incident occurred in Wilhelmshaven, Germany, in 2005. To support a large offshore wind turbine, a bucket foundation was to be installed by both suction and skirt tip injection. The bucket had a skirt length of 15 m, a diameter of 16 m and

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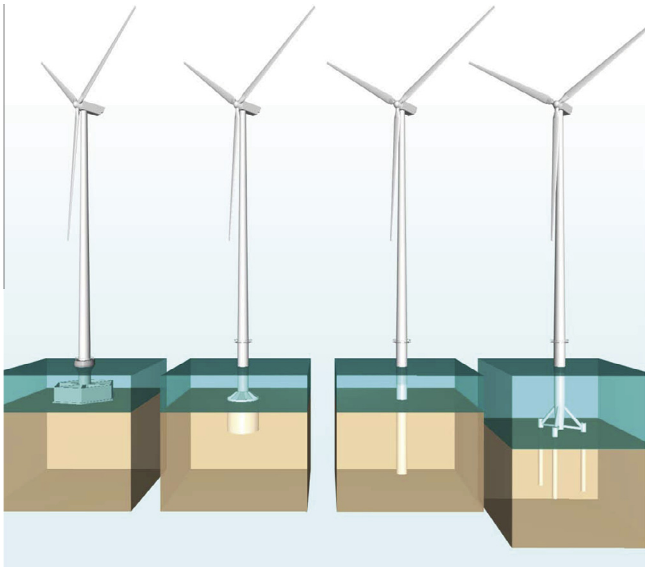

Fig. 1. Foundation concepts for offshore wind turbines. From the left: gravitational foundation, bucket foundation, monopile foundation, and tripod foundation [1].

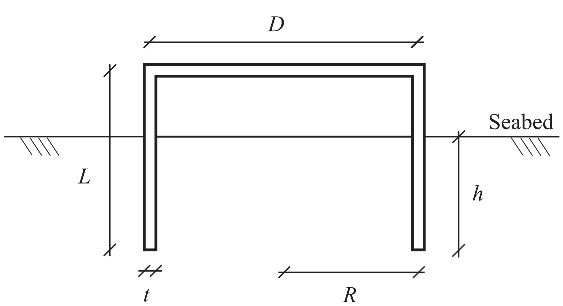

Fig. 2. Bucket dimensions.

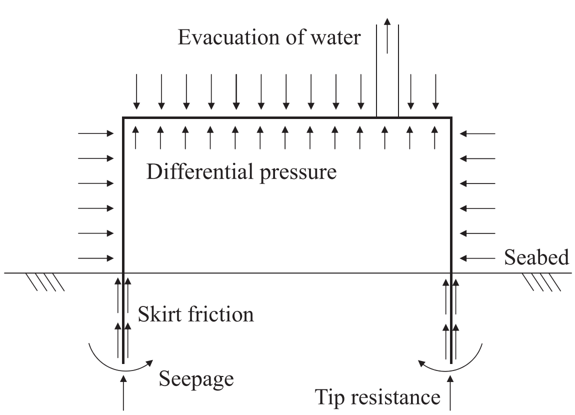

Fig. 3. Principle sketch of the downward pressure on lid and skirt due to suction.

a skirt thickness of 25 mm. As the skirt had penetrated 6.8 m into the soil, the bucket foundation buckled. Consequently, the installation failed completely. A photograph of the collapsed bucket foundation is shown in Fig. 4. This incident emphasises the importance of detailed buckling analyses of the bucket foundation.

Several analytical expressions for the structural buckling pressure of circular cylindrical shells exist, cf. e.g. [3,4]. Nowadays, cylindrical shell structures are designed according to e.g. DNV [5] or Eurocode [6] standards. These standards require assumptions of idealised boundary conditions like pinned, fixed or free. None of the design regulations account for the lateral restraints offered by the surrounding soil. Recently, this lateral restraint offered by the soil has been modelled by elastic Winkler springs [7] or Pasternak type foundations [8].

Fig. 4. Buckling failure in Wilhelmshaven 2005.

Neither of the above mentioned analyses takes the lateral restraints offered by the soil into account by means of advanced non-linear finite element solutions. It may be beneficial to perform some more refined analyses with more realistic boundary conditions modelled by a continuum. An attempt to do so was performed by Pinna et al. [9] for suction caissons in clay. The soil was modelled by both an elastic model and an elasto-plastic Tresca model. However, idealised assumptions of the end boundary conditions were still made. Further, only the lowest eigenmode was considered. The authors have introduced an advanced three-dimensional non-linear finite element analysis, using the commercial finite element package ABAQUS [10]. Previous work by the authors has shown that introducing an imperfect geometry based on the first mode shape from a linear eigenvalue buckling analysis can increase the buckling load significantly [11]. In this paper, not only the first mode shape is considered, but several imperfect geometries are considered in order to find the most critical mode shape. Further, the numerical results are compared with current standards for evaluating buckling loads.

2. Methods of analysis

Different design methods are allowed in Eurocode 1993-1-6 *Design of steel structures - Strength and Stability of Shell Structures* [6]. The different methods are listed in Table 1 and contain both hand calculations based on classical buckling theory and global numerical methods. The first method is based on membrane theory where the rest rely on numerical methods with different levels of complexity.

In this paper, the analytical membrane theory as well as the theory corrected by Eurocode and DNV expressions are considered. The numerical analysis conducted consists of LBA and GMNIA, cf.