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Upper bound solutions of vertical bearing capacity of skirted mudmat in sand

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ABSTRACT

The mudmat is an important foundation form for deep water oil and gas engineering in the sub sea production system. The mudmat has a wide application prospective because of its shallower buried depth and convenient construction in the ocean. The existence of skirts, which are set up at the bottom of the mudmat in order to adapt to the requirements of the foundation slip resistance, increases the difficulty in the vertical bearing capacity calculation of the mudmat. The mudmat is simplified to a skirted strip foundation in this paper, and the mechanisms have been proposed according to the surcharge soil assumption. The upper value of the vertical bearing capacity of the mudmat is obtained by the upper bound theorem of the limit analysis. The soil damage rate as a new empirical parameter concerning the combined action between the skirts and the inner soil of the foundation has been defined. The value of the soil damage rate indicates the range of soil failure. The relationship between the soil damage rate and the aspect ratio is determined for the mudmat using a two-dimensional simplified analysis. The relationship of the bearing capacity factors N_q and N_γ with the friction angle is also discussed under the different soil damage rates.

1. Introduction

The subsea production systems that are applied in the deep sea are the primary equipment used in the exploitation of deep sea oil and gas resources. The subsea production system is installed on the subsea under complex geological conditions. Therefore, the stability of the foundation is a prerequisite to ensure the safe operation of the entire system. Mudmats, which are a type of shallow foundation and have historically been used to provide temporary stability for fixed-jacket platforms in relatively shallow water, are now widely employed for deep-water subsea production infrastructure, such as for manifolds, end terminations and in-line structures for pipelines. The bearing capacity calculation method of mudmat foundation is different from the traditional shallow foundations. The skirted construction which is located around the bottom of the mudmat foundation strengthens the bearing capacity of the foundation. The behaviour of the skirted foundations for such structures has been studied by several researchers using both numerical and physical modelling [1–7]. The response of individual skirted foundations to combined vertical, horizontal and moment loadings were obtained by Bransby and Randolph [1]. Byrne and Houlsby described experimental investigations into the vertical loading response of a bucket foundation [2]. White et al. described an investigation in which solid and perforated mudmats were installed into soft clay [3]. Static stability mainly against sliding of a typical, relatively large skirted gravity structure were investigated using three-dimensional finite element modelling by Dewoolkar et al. [4]. Results from small strain finite-element analyses were used to quantify the immediate and time-dependent response of circular skirted foundations to uniaxial vertical loading by Gourvenec and Randolph [5]. Experiments have been undertaken using a six degree of freedom loading rig to investigate the capacity of grillage foundations under combined Vertical (V), Horizontal (H) and Moment (M) loading, as experienced in offshore conditions by Tapper et al. [6]. Feng et al. presented an alternative design method, based on failure envelopes derived from an extensive programme of three dimensional finite-element analyses, focusing on the sliding and rotational capacity of the foundation [7]. A simplified approach for predicting the ultimate limit state of mudmat foundation under six degrees-of-freedom, based on failure envelopes, were obtained from extensive finite element analyses by Feng and Gourvenec [8]. Two- and three-dimensional finite element analyses were performed to identify the optimal internal skirt spacing for the maximum undrained capacity of subsea

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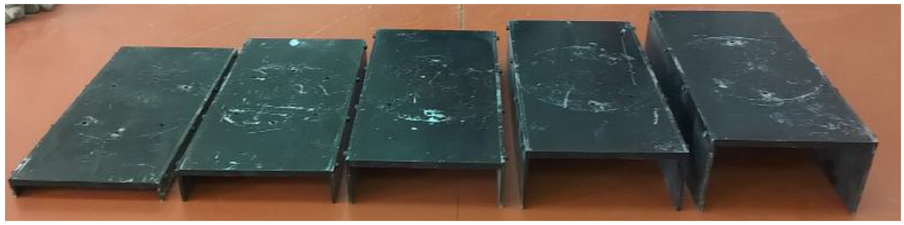

Fig. 1. Mudmat models.

skirted mudmats by Feng et al. [9]. A generalised framework was presented for predicting the consolidated undrained capacity of rectangular mat foundations on normally consolidated soft clay under combined loading in six degrees of freedom as a function of relative preload and degree of consolidation by Feng and Gourvenec [10]. The effect of soil–foundation interface condition on the undrained capacity of rectangular mudmat foundations under loading in six degrees of freedom were investigated by Shen [11]. The results were presented systematically to quantify shape effects on undrained capacity of rectangular mudmat foundations under multi-directional loading for a practical range of soil shear strength heterogeneity by Feng et al. [12]. X. Feng et al. presented guidance on the minimum number of shear keys required to achieve optimal capacity of square and rectangular skirted foundations under undrained generalised six degree-of-freedom loading in soft soils with linearly increasing shear strength with depth [13]. The above papers usually focus on cohesive marine deposits, and these studies have been focused on predicting the undrained shear strength behaviour of the deposits that are enclosed and overlain by mudmat foundations. In the process of exploiting offshore oil and gas resources of China, sand was found on the subsea. However, studies on the behaviour of mudmat foundations resting on such soils and carrying vertical compression loads have been relatively limited in the literature. A modification in load-settlement behaviour resulting from having skirts and grillages was demonstrated by such studies based on 1-g physical model tests [14–18].

The mudmat is a shallow foundation from the perspective of foundation separation. For shallow foundations, the more classic formula for calculating vertical bearing capacity has been Terzaghi's, Meyerhof's, Hansen's and Vesic's and other formulas [19–22]. The mudmat foundations always have skirts around the basal edge to bear the horizontal and moment loading. However, the bearing mechanism has been changed compared with the traditional shallow foundation because of the skirts. In this paper, bearing capacity model tests are carried out to estimate the vertical bearing capacity of mudmat foundations in sand. The skirted mudmat foundation is simplified as a skirted strip foundation, and the vertical bearing mechanism is presented for the skirted mudmat foundation. The formula has been derived through the upper bound theorem of the classical plasticity theory. The soil damage rate η_M is specified as a new empirical parameter in the formulas, which can effectively reflect the interaction between the skirts and the soil. The range of the soil damage rate is obtained through the vertical bearing capacity experiments. The relationship between the bearing capacity factors N_q and N_γ with the friction angle is also discussed for different height-diameter ratios H/B.

2. Model tests

The existence of skirted construction makes the bearing capacity mechanism of mudmat foundation more complex. Whether the soil inside skirt is restrained is uncertain. Therefore, the bearing capacity model tests were carried out to estimate the vertical bearing capacity of mudmat foundations in sand. The difference between mudmat and strip foundations is due to the vertical bearing capacity mechanism. The bearing capacity model tests were carried out at Tianjin University. The test box consists of a rigid steel construction, with inner horizontal dimensions of 1000 × 1000 mm and an inner total depth of 1000 mm. The models were loaded using a three-degree-of-freedom loading rig (Fig. 1). The mudmat foundation models (Fig. 2) were made from steel and had an external diameter of 200 mm, a skirt wall thickness of 5 mm, and skirt lengths of 20, 40, 60, 80, and 100 mm. These dimensions resulted in height-diameter ratios, H/B, of 0.1, 0.2, 0.3, 0.4, and 0.5, respectively. A three degree-of-freedom loading rig has been developed at Tianjin University. The unique feature of this apparatus is that an arbitrary displacement path can be applied to the model footing using computer controlled stepper motors. The independent control of the three components of displacement is accomplished by using separate bearing arrangements and by superposition of the different motion systems. The vertical, horizontal and moment displacement ranges are 600 mm, 300 mm and 20°, respectively. Fig. 2 shows the loading rig and the associated equipment.

Fig. 2. Three-degree-of-freedom loading rig.

Sand was chosen as the soil medium because of the coastal conditions of Jiangsu Province. Quick direct shear tests were performed to determine the strength parameters of the soil. As a result, the friction angle of the soil was obtained under the total stress condition. The geotechnical properties of the sand are summarised in Table 1.

Displacement controlled tests were conducted under a constant velocity of dh/dt = 3.0 mm/min. Fig. 3 shows five test results as examples in the load-settlement curves. The right curve corresponds to the model with H/D = 0.5, and the left curve corresponds to the model with H/D = 0.1. In the initial phase, the load and the settlement increases linearly. When the settlement is 11 mm, the load