Ocean Engineering 135 (2017) 221–235

Contents lists available at ScienceDirect

Ocean Engineering

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

Shape effects on undrained capacity of mudmat foundations under multi-directional loading

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ARTICLE INFO

Keywords:
Seabed foundations
Failure
Bearing capacity
Subsea systems
Geotechnical design

ABSTRACT

The results presented in this paper systematically quantify shape effects on undrained capacity of rectangular mudmat foundations under multi-directional loading for a practical range of soil shear strength heterogeneity. Mudmat foundations are extensively deployed to support infrastructure for subsea production systems, are typically rectangular in plan, ranging from square to a width-to-length aspect ratio of 0.2, and are subject to multi-directional loading from the attached pipelines and jumpers. The load-carrying capacity of rectangular mudmats on deposits with undrained shear strength linearly increasing with depth is analysed by the finite-element method, and presented in the form of 'failure envelopes'. The results show that shape effects are significant and are dependent on the degree of soil strength heterogeneity and loading direction (relative to the orthogonal axes of the mudmat). General algebraic expressions are established that systematically define the coupled effects of width-to-length aspect ratio of the mudmats and the degree of strength heterogeneity of the subsoil. Expressions describing the uniaxial ultimate limit states and the normalised failure envelopes under multi-directional loading can be programmed into a calculation tool for automating optimised mudmat sizing for a range of foundation geometry and soil strength heterogeneity.

1. Introduction

Subsea shallow foundations, referred to as mudmats, are widely employed to support subsea infrastructure, such as pipeline end terminations and manifolds for offshore oil and gas developments. Mudmat foundations are generally rectangular in plan, featuring peripheral and internal 'skirts' in soft seabed conditions to distribute the foundation loads to deeper stronger soil. The required footprint area of a subsea mudmat to ensure load-carrying capacity is governed by the multi-directional load response, which is dependent on the coupled effects of foundation aspect ratio and soil strength heterogeneity of the seabed.

The bearing capacity of rectangular mudmats is usually based on the plane strain solution for an infinitely-long strip foundation (Davis and Booker, 1973; Terzaghi, 1943). The maximum vertical load V_d that a rectangular foundation can support under undrained conditions is conventionally expressed by Eq. (1) (ISO, 2003)

$$V_d = F\left(N_c s_{u0} + \frac{\rho B'}{4}\right)K_c A' \tag{1}$$

Where, F is the correction factor given as a function of foundation roughness and $\rho B'/s_{u0}$, ρ is the gradient of the increase of undrained shear strength with depth; s_{u0} is the undrained shear strength of the soil at foundation level, N_c is the plane strain bearing capacity factor for uniform shear strength (2+π), B′ is the minimum effective lateral foundation dimension, A′ is the effective area of the foundation depending on the load eccentricity, and K_c is the superposing modification factor accounting for load inclination, foundation shape, etc. An empirical shape factor to consider the end effects of the rectangular foundations is the most widely adopted Skempton's expression (Skempton, 1951), which adjusts bearing capacity linearly with the width-to-length aspect ratio; for a square foundation the ultimate limit state is taken as 20% higher than for a strip foundation. Most previous research on the shape factors for bearing capacity of rectangular foundations has focused on the constant undrained shear strength. Various methodologies have been employed, including plastic limit analysis (Michalowski, 2001), finite-element analysis (Gourvenec et al., 2006; Merifield and Nguyen, 2006; Zhu and Michalowski, 2005) and finite-element limit analysis (Lyamin and Sloan, 2000; Salgado et al., 2004). However, the deep-water seafloor is generally fine-grained soil

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http://dx.doi.org/10.1016/j.oceaneng.2017.02.033
Received 16 May 2016; Received in revised form 5 December 2016; Accepted 27 February 2017

with undrained shear strength linearly increasing with depth. In addition, the external loads applied to subsea mudmats are multi-directional rather than purely vertical, resulting from installation and operational forces from pipeline and jumper connections to the structures supported by mudmats. For combined loading conditions, Gourvenec (2007) examined shape effects on undrained load-carrying capacity of rectangular foundations under co-planar loading on soil with uniform undrained shear strength with depth. The response of rectangular mudmats subjected to fully three-dimensional loading was investigated by Feng et al. (2014) for subsoil with varying undrained shear strength heterogeneity. However, only the mudmats with aspect ratio of 0.5 were considered since that the mudmat size was constrained by the particular dimension of the rectangular opening, i.e. the moon-pool, on the installation vessel through which the mudmats are laid down onto the seabed. Other constraints over dimensions of pre-installed mudmats include the stinger structure for S-lay and the geometrical envelope of the tower for J-lay (Fontaine and Dilosquer, 2014), and thus may vary with a specific type of installation vessel. Furthermore, for the recent concept of post-installed mudmats presented in Fontaine and Dilosquer (2014), the constraint of an installation vessel over the dimension of the mudmats can be relaxed by integrating the mudmat installation with the pipe-laying process. Therefore, the aspect ratio and dimensions of rectangular mudmats may be variable, yet multi-directional load-carrying capacity has not been systematically established for rectangular foundations with varying aspect ratios.

The work presented in this paper examined the undrained load-carrying capacity of rectangular mudmats of varying aspect ratios on soil with varying degrees of strength heterogeneity under general combined loading conditions. The finite-element (FE) method was employed and the load-carrying capacity of the mudmats is presented in the form of failure envelopes, which allows for explicit consideration of the independent load components, foundation geometry and soil conditions, rather than superposing modification factors. The effects of foundation aspect ratio and degree of soil strength heterogeneity on the shape of the failure envelopes are systematically examined. General algebraic expressions are proposed to describe the normalised failure envelopes, enabling developing an automatic calculation tool for routine use for the geotechnical design of subsea mudmats in deep water.

2. Boundary conditions

The sign convention for each component used in this study is shown in Fig. 1. The notation adopted for loads is summarised in Table 1. The ultimate vertical, horizontal and moment capacities are defined as the pure load-carrying capacity in the absence of other loading. Rectangular mudmats with width-to-length aspect ratio of B/L=0.2, 0.33, 0.5, 0.75 and 1 (square) were considered to cover the range in engineering practice. The width B of the mudmat is kept at 5 m and the length varies according to the prescribed aspect ratio. The shallowly embedded skirted mudmat was modelled as an equivalent surface foundation with a full-tension skirt-soil interface, as commonly adopted to conceptually represent the effect of skirts on uplift and overturning resistance (Bransby and Randolph, 1998; Gourvenec and Randolph, 2003; Taiebat and Carter, 2000; Tani and Craig, 1995). The idealisation is not expected to affect the underlying mechanisms accompanying failure, but can underestimate capacity by neglecting the work done by shearing in the soil above skirt tip level. Recent studies found that the shape of the normalised V-H, V-M, M-M and H-M failure envelopes is insensitive of the skirt depth of the mudmat foundations (Feng et al., 2014). The effect of embedment depth on the normalised failure envelopes for biaxial horizontal loading (H-H) has been assessed thoroughly in Feng et al. (2017). Therefore, the depth effect is not explicitly investigated in current study. The undrained soil shear strength s_u was assumed to be uniform or increase linearly with depth according to $s_u=s_{u0}+\rho z$, as shown in Fig. 1, where s_{u0} is the shear strength at mudmat level and ρ is the gradient of soil shear strength. The degree of soil strength heterogeneity is defined as $\kappa=\rho B/s_{u0}$, ranging from 0 (uniform soil) to 20, to bracket field conditions. The lower end of the range is relevant to over-consolidated deposits and the latter end of the range to softer normally consolidated deposits, providing in either case the drainage conditions and loading rate are such that the soil response remains undrained. For the uniform soil, the undrained shear strength is kept constant at 5 kPa, whereas the gradient of the soil undrained shear strength maintains 1 kPa/m and the shear strength at mudmat level s_{u0} is determined according to the prescribed value of κ for a heterogeneous strength profile. The soil parameters employed in the FE models are listed in Table 2. All results are presented in terms of dimensionless quantities as summarised in Table 1 and are independent of the absolute mudmat dimensions and the adopted soil shear strength profiles. However, additional analyses are carried out using different combinations of B, ρ and s_{u0} to reassure the readers of the normalisation strategy as shown later in this paper.

The mudmats are subjected to general combined vertical (V), horizontal (H) and moment (M) loading. The torsion is excluded from present analyses but the effect of torsion is assessed later in this paper using the proposed design approach in Feng et al. (2014) for rectangular mudmats under fully three-dimensional loading.

3. Finite element model

3.1. Geometry

All the finite element analyses were carried out using the software ABAQUS (Dassault Systèmes, 2011). Five fully three-dimensional models were established to investigate the effect of varying aspect ratios on bearing capacity. Each mesh maintained the same geometry and discretisation on the central plane through the centroid of the mudmat. More elements were required in the longitudinal direction of the more slender mudmats to maintain a consistent element size across the models. For example, the mesh for the B/L=0.2 mudmat (Fig. 2a) comprises 61,300 linear 8-node continuum hybrid elements (refer to element type C3D8H in the ABAQUS element library), and the mesh for the B/L=1 mudmat comprises 41,500 elements. The hybrid element formulation uses a mixture of displacement and stress variables (as opposed to solely displacement) to approximate the equilibrium equations and compatibility conditions. Hybrid elements are recommended for modelling the response of incompressible and near-incompressible materials (such as is appropriate for undrained soil conditions). Only the half view of each mesh is shown in Fig. 2 to illustrate the mesh consistency on the mid-point central plane.

The mesh boundaries were set a distance of 3B from the edges of the mudmat and 3B beneath the mudmat, sufficiently remote from the mudmat and applied loading that the failure mechanisms were unaffected. Mesh nodes at vertical boundaries were constrained to prevent out-of-plane displacement, while those at the base of the mesh were fully constrained in all three coordinate directions. Relatively fine mesh was provided in the vicinity of the edges of the mudmat (~1%B) and immediately below the mudmat (~0.3%B) to precisely capture the failure loads and mechanisms.

The model for a strip foundation was also built as a reference case with the same geometry and mesh discretisation on the mid-point central plane as shown in Fig. 2 for rectangular mudmats.

3.2. Material properties and interface conditions

The undrained soil condition was represented with a linear elastic perfectly plastic constitutive law obeying the Tresca failure criterion. A constant modulus ratio of $E_u/s_u=1000$ was prescribed to give a relatively high rigidity index G/s_u of 336, where G is the shear modulus of the soil, enabling failure loads to be mobilised with relatively small deformation to aid numerical convergence by avoiding excessive iterations triggered by mesh distortion. To avoid numerical difficulties