Computers and Geotechnics 88 (2017) 152–163

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Application of a memory surface model to predict whole-life settlements of a sliding foundation

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ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 17 March 2017
Accepted 19 March 2017

Keywords:
Settlement
Cyclic loading
Offshore engineering
Soil modelling
Memory surface

ABSTRACT

In this paper a novel modelling procedure is proposed to estimate whole-life settlements of tolerably mobile sliding foundations. A new kinematic hardening-critical state-state parameter constitutive model, the Memory Surface Hardening model, is implemented in a one-dimensional analysis to predict accumulated vertical settlements under drained lateral cyclic loading. The Memory Surface Hardening model performance is compared with the Modified Cam Clay and Severn-Trent Sand models. The Memory Surface Hardening model is adopted to simulate available experimental data from centrifuge tests to predict the settlement of a sliding foundation at the final stable state (i.e. no further volume changes occur).

1. Introduction

Sliding foundations are a novel concept to meet the increasingly challenging demand to limit the footprint of subsea mudmats. In contrast to the traditional paradigm that foundations remain stationary and resist all the applied loads, sliding foundations are designed to move tolerably across the seabed to relieve some of the applied loads, thus requiring a smaller footprint. Sliding displacements are caused, and also limited, by expansion and contraction of attached pipelines ([1–3]). In general, magnitudes of displacement are sufficient to cause shear failure between the foundation and the soil, where the mobilised ratio of shear stress to normal effective stress is greatest.

Subsea mudmats are shallow, mat-style foundations used to support pipeline infrastructure for offshore hydrocarbon developments. Foundation loads derive from the self-weight of the mat, the supported structure and thermal expansion and contraction of the attached pipelines. Increasing operational loads coupled with softer seabeds has resulted in traditional subsea mudmat designs exceeding the installation capacity of pipelaying vessels. The expense of an additional heavy lift vessel on site to install over-sized mudmats can be prohibitive. Sliding foundations offer a potential solution to this impasse ([1–3]).

Observations of performance of a sliding foundation on soft clay from a programme of centrifuge model tests are reported by Cocjin et al. [2]. The considered sliding mudmat comprised a rectangular rough-based mat of breadth to length aspect ratio of 0.5 and was provided with edge 'skis' to facilitate sliding (rather than overturning that may lead to overstressing of the pipeline connections). A schematic representation of the generalized geometry is presented in Fig. 1, also showing an attached pipeline connection. The tests involved a number of cycles of undrained sliding with intervening periods of consolidation. The model data showed settlement of the mat during each period of consolidation resulting from dissipation of shear induced pore pressures generated during the preceding sliding event. The accumulated mat settlements reduced with each slide, ultimately reaching a stable state condition with no further volume change in the soil. This stable state was shown to be equivalent to the drained state [4].

This last observation is illustrated in Fig. 2, through an analysis of a strain-imposed cyclic simple shear test under constant total vertical stress conditions using the Modified Cam Clay model [5]. Results compare the stress-volume changes under drained cycles of loading and undrained cycles of loading with intervening periods of consolidation. It is evident that the volumetric behaviours are comparable and the final stable state from the two simulations

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http://dx.doi.org/10.1016/j.compgeo.2017.03.014

Nomenclature

A	geometrical distance to calculate the stress distribution beneath the foundation
A_d	flow rule multiplier
B	foundation width
C	geometrical distance to calculate the stress distribution beneath the foundation
D	geometrical distance to calculate the stress distribution beneath the foundation
L	foundation length
b	distance between the current stress state $\boldsymbol{\sigma}$ and the conjugate one on the bounding surface $\boldsymbol{\sigma^B}$
b^M	distance between the current stress state $\boldsymbol{\sigma}$ and the conjugate one on the memory surface $\boldsymbol{\sigma^M}$
b_{max}	maximum value of b
β	parameter controlling the amount of settlement in the first slide
d	dilatancy flow rule
δ_v	vertical displacement
e	void ratio
e_{CSL}	intercept of the critical state line in e-ln p′ space at p′ = 1 kPa
ε_v	vertical strain
f_Y	yield surface
f_B	bounding surface
f_M	memory surface
h	layer thickness
H	hardening modulus
k	undrained shear strength gradient
k^*	parameter controlling the relationship between state parameter and available strength
k_d	stress-dilatancy parameter
k_0	lateral earth pressure
M_{cv}	critical state stress ratio for compression
N_{cV}	bearing capacity factor
N_{cyc}	number of cycles
p'	effective mean stress
p'_c	consolidation pressure
p_{ref}	reference pressure (=100 kPa)
q	deviatoric stress
q_{op}	foundation vertical pressure
q_u	ultimate bearing capacity
R	ratio of sizes of yield surface and bounding surface
s_{um}	undrained shear strength at the surface
z	depth
γ'	effective unit weight
η	stress ratio
κ	slope of re-compression line in the e-ln p′ space
λ	slope of the critical state line in e-ln p′ space
μ	constitutive parameter affecting the MSH model response in cyclic conditions
v	Poisson's ratio
$\boldsymbol{\sigma}$	stress state
$\boldsymbol{\sigma^B}$	conjugate stress point on the bounding surface
$\boldsymbol{\sigma^M}$	conjugate stress point on the memory surface
σ'_v	effective vertical stress
ς	constitutive parameter affecting the contraction of the memory surface
τ_{max}	maximum shear stress under cyclic loading
ψ	state parameter
$\Delta\tau_{cyc}$	cyclic amplitude in each soil layer

converge. A further check is performed by comparing the variation of the void ratio with the number of cycles for the performed simulations. The trends are similar, which confirms that the soil response is comparable.

It can therefore be surmised that consideration of drained sliding and associated (drained) volumetric strain is an appropriate approximation for undrained generation and subsequent dissipation of shear induced excess pore pressures. On this assumption, this study investigates the volumetric response of drained lateral cyclic loading of a sliding foundation. Three constitutive models are adopted to estimate vertical settlements over the whole-life of a sliding foundation; predicted results are compared with available data from centrifuge tests performed at the University of Western Australia – Centre for Offshore Foundation Systems (UWA-COFS) [2].

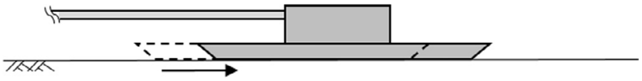

Fig. 1. Layout of the sliding foundation concept.

2. Analysis set up and soil model

2.1. Analysis set up

The framework of the 1-D analyses considering a sliding mudmat of width B resting on half-space soil is shown in Fig. 3. The overall soil response under the shearing imposed by the sliding mudmat is computed through a layer-by-layer summation, by

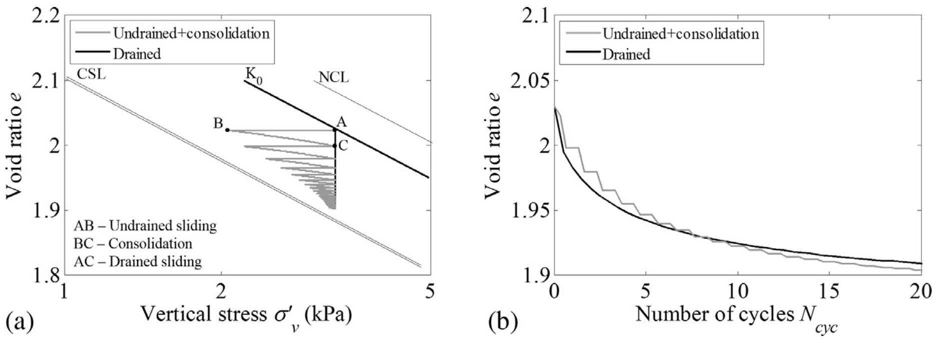

Fig. 2. Comparison of (a) volumetric response and (b) variation of void ratio with the number of cycles of a soil element close to the interface between the sliding mudmat and the soil (z/B = 0.05, with z being the depth and B being the width of the foundation), subjected to cyclic simple shear under constant total vertical stress by imposing either undrained loading with intervening consolidation or drained loading conditions, using the Modified Cam Clay constitutive soil model [5].