Computers and Geotechnics 68 (2015) 208–219

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Analytical and numerical modelling of non-driven disc on friction material

Moosa Esmaeili, Ana Ivanović *

School of Engineering, College of Physical Sciences, King's College, Fraser Noble Building, University of Aberdeen, AB24 3UE, United Kingdom

ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form 2 April 2015
Accepted 9 April 2015

Keywords:
FE modelling
Contact
Granular material
Interaction
Boundary value problem and Coupled Eulerian Lagrangian (CEL)

ABSTRACT

The analysis of boundary value problems associated with large deformations are often difficult to solve with traditional Lagrangian finite element methods. Since large deformation problems suffer from mesh distortions especially in contact problems, the convergent solution is difficult to obtain. Accordingly, the Coupled Eulerian–Lagrangian (CEL) approach is employed, using the finite element code, Abaqus/Explicit, to assess the influence of the soil strength and rigid object geometry on the relationship between the forces acting on the object and its sinkage. An analytical model is also presented, which predicts the drag and vertical forces acting on the rigid object, towed in non-cohesive material. This study is only focused on predictive tools for the modelling of the interaction between a non-driven disc and deformable soil. Analytical and numerical results are compared with the experimental results available in the literature and those obtained from scaled model sections of a disc assembly and single disc and generally good agreement is obtained.

1. Introduction

The analysis of the interaction between a rigid object and stratum constitutes one of the main topics of contact mechanics [1]. The associated deformation of the stratum and the reaction force on the rigid object when an object is towed or pushed within the deformed material is the central part of many engineering applications. Such applications include iceberg interaction with the seabed [2,3], vehicle mobility assessment [4,5], wheel-soil interaction [6–8], damaging effects of towed demersal gear on benthic organisms [9–12] and assessment of blades and ploughs cutting the soil [13,14].

In this paper, a theoretical model which accounts for three-dimensional effects was developed to expand on existing analytical and semi-analytical approaches for modelling soil-wheel interaction, which are amply illustrated in the literature and summarized in [6,7]. Most analytical or semi analytical approaches for modelling the soil-object interaction consider only plane or axisymmetric objects and simplified material models, for example an object indentation into perfectly plastic frictional and cohesive material [15–20]. Analytical models that consider fully three-dimensional soil-object interaction have been proposed only recently for cohesive–frictional soil [6,7]. The analytical approach was formulated for steady rolling based on a rigid-perfectly plastic Mohr–Coulomb material which provides prediction of the force-penetration relationship for purely frictional materials. This model also makes it possible to compare the numerical and experimental results with results of an analytical approach in which the elastic properties and dilatancy of soil are disregarded.

An appropriate tool for obtaining a solution for boundary value problems is the finite element method, which has been used increasingly in recent years to study object-soil interaction [2,6–8,21,22]. Application of the classical finite element method to solve such boundary value problems is difficult regarding large deformation. It is evident that the numerical modelling of large deformation with the classical finite element method based on the Lagrangian formulation has many disadvantages, particularly in contact problems, where a convergent solution is very difficult to accomplish. The limitations of the Lagrangian mesh were reported by Belytschko et al. [23] where convergence problems and even more importantly, extreme mesh distortions due to large deformation were highlighted. The Lagrangian approach was used in a similar study [24] but was proven sensitive to mesh distortion and was therefore deemed not sufficient for these problems. A potential numerical method that may overcome the shortcomings of the Lagrangian finite method is the discrete element method [25,26] but this method is not suitable for modelling the boundary value problems with large dimensions. This

* Corresponding author. Tel.: +44 1224273265.
E-mail addresses: moosa.esmaeili@gmail.com (M. Esmaeili), a.ivanovic@abdn.ac.uk (A. Ivanović).

http://dx.doi.org/10.1016/j.compgeo.2015.04.007
0266-352X/

Nomenclature

d	disc diameter	f	penalty force
t	disc thickness	θ	angle of the rotation
$\bar{t}$	dimensionless disc thickness $(\bar{t} = \frac{t}{d})$	α	angle of contact surface inclination
z	sinkage	β	angle of backfill surface
$\bar{z}$	dimensionless sinkage $(\bar{z} = \frac{z}{d})$	η	angle of force inclination
u	horizontal displacement	Ω	angular displacement
$\bar{u}$	dimensionless horizontal displacement $(\bar{u} = \frac{u}{d})$	μ	friction coefficient of the soil/rigid body
F_H	horizontal drag force	c	cohesion
$\overline{F}_H$	dimensionless horizontal drag force $(\overline{F}_H = \frac{F_H}{\gamma t d^2})$	E	Young modulus
F_V	vertical reaction of force	$\overline{E}$	dimensionless Young's modulus $\left(\overline{E} = \frac{E}{\gamma d}\right)$
$\overline{F}_V$	dimensionless vertical reaction of force $(\overline{F}_V = \frac{F_V}{\gamma t d^2})$	ν	Poisson's ratio
W	weight of the rigid body	ψ	dilation of soil
$\overline{W}$	dimensionless weight of the rigid body $\left(\overline{W} = \frac{W}{\gamma t d^2}\right)$	φ	angle of internal friction
P_p	passive pressure	γ	unit weight of soil
F_f	frictional force	δ	wall angle of friction

is due to the large number of discrete elements, where the scaling and calibration of large dimensions in the numerical model is very difficult. To deal with this problem the Coupled Eulerian Lagrangian (CEL) approach (cf. [27]) came into consideration to overcome the Lagrangian mesh distortion associated with the large deformation analyses. The CEL method is often applied in fluid mechanics and attempts to capture the strengths of the Lagrangian method and the Eulerian formulation to simulate deformable parts.

The application related to this contact problem has been prompted by the interaction between fishing gear elements and the seabed and their environmental and ecological impact on the benthic and the influence this contact makes to the overall drag force and consequently to the fuel efficiency of the fishing. A number of studies reported on the damaging effects of towed demersal gear on benthic organisms and habitats and on the water column [9–12] however very few have tried to address the physical process associated with those processes. Similarly, most studies in relation to gear drag have focused on the hydrodynamic forces acting on the gear and the associated net deformations [28,29] while bottom contact forces have not been investigated to the same extent. Both contacts are important in order to fully understand the ecological and environmental impact of towed demersal fishing gears, and therefore it is important to understand the physical mechanisms involved. The interaction between the rockhopper in the fishing gear assembly, which was produced from sections of rubber discs joint together, and seabed was investigated in [30] in which a unique expression of the towing force of the rockhopper segment is derived as a function of drag force of a single disc. However, the numerical model presented in [30] is limited to fixed penetration cases where the component was not able to rotate or freely penetrate into the seabed. The current study extents the previous model for a more complex case i.e. the interaction between the non-driven disc and soil where the disc is able to move freely into the soil and rotate when towed along the soil.

The main focus of this study is on modelling a general case of a non-driven disc in order to appreciate the movement of the soil around the disc and consequently any influence the various types of soil, disc size and weight may have on the drag and vertical forces investigated. This paper therefore attempts to theoretically and numerically analyse the process of a non-driven disc interacting with plastically deformable material, and the physical testing considered for comparison.

2. Numerical model

2.1. Numerical methods

Due to the large deformation of the material associated with the interaction of the non-driven disc and soil, the classical finite element method (such as Lagrangian finite element method) leads to unacceptable distortion of mesh. In order to eliminate this shortcoming, the Coupled Lagrangian Eulerian method (CEL) has been considered [27]. In order to justify the benefits of the CEL model over the other methods the major differences between the Eulerian and Lagrangian approaches are: (i) the movement of the continuum in the Lagrangian element is specified as a function of time and material while in the Eulerian element it is specified as a function of spatial coordinates and time (ii) the nodes in Lagrangian element move together with the material while in Eulerian element they are fixed within Eulerian domain while tracing the motion of the material. The latter method therefore causes no distortion of the mesh resulting in a material being able to flow freely through the Eulerian elements.

The main advantage of the CEL method is that the Eulerian mesh can deform without any mesh distortion and new boundaries can be formed or eliminated. The CEL method has proved successful in dealing with large deformation, moving boundaries and in reducing numerical diffusion. The flow of the material in the mesh is tracked by computing its Eulerian volume fraction (EVF). The Eulerian elements are represented by the portion of material filled i.e. EVF = 1 if the element is completely filled and EVF = 0 when the element is empty. For example, the Lagrangian part can move through the Eulerian mesh without any resistance when EVF = 0.

This method attempts to capture the strengths of the Lagrangian to simulate rigid body and the Eulerian to simulate the deformable part of the model. In this study, a rigid body (disc) and deformable part (soil) are modelled using the CEL method where the soil and rigid object are defined by Eulerian and Lagrangian meshes, respectively.

2.2. Model description

The modified Mohr–Coulomb constitutive model [c.f. 31] is employed to simulate the inelastic behaviour of purely frictional material which is based on the non-associated flow rule and is governed by the friction angle φ, dilation angle ψ and cohesion c, described in detail in [30]. Numerical instability occurs when using purely frictional soil i.e. $c = 0$ and it appears as a convergence