International Journal of Solids and Structures 51 (2014) 3449–3460

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Numerical modeling of coupled seabed scour and pipe interaction

Hossein Fadaifard, John L. Tassoulas *

Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, Structural Engineering, Mechanics, and Materials, 301 E Dean Keeton St., Stop C1748, Austin, TX 78712-1068, USA

ARTICLE INFO

Article history:
Received 8 December 2013
Received in revised form 20 April 2014
Available online 21 June 2014

Keywords:
Seabed scouring
Soil flow
Soil–structure interaction
Arbitrary Lagrangian Eulerian

ABSTRACT

Scouring of the seabed by ice masses poses great threat to structural integrity and safety of buried structures such as oil and gas pipes. Large ridge motions and large seabed deformations complicate study of the seabed scouring and pipe interaction using classical Lagrangian methods. We present a new numerical approach for modeling the coupled seabed scour problem and its interaction with embedded marine pipes. In our work, we overcome the common issues associated with finite deformation inherently present within the seabed scour problem using a rheological approach for soil flow. The seabed is modeled as a viscous non-Newtonian fluid, and its interface described implicitly through a level-set function. The history-independent model allows for large displacements and deformations of the ridge and seabed, respectively. Numerical examples are presented to demonstrate the capabilities of the method with regard to seabed scouring and the ensuing large soil deformation.

1. Introduction

The seabed scouring process (also referred to as seabed gouging, furrowing, plowing, scoring, scarping) describes the active physical process that takes place when ice masses come in contact with the seabed. Grounding of ice masses and subsequent scouring of the seabed occur when the draft exceeds the water depth. This interaction produces long gouges and basin-shaped depressions on the seabed, which are common marked features in shallow marine shelves with water as deep as 27 m (Carmack and Macdonald, 2002; Miller et al., 2004). Seabed scouring is not limited to shallow depth as evidence of scouring marks is visible in water depths of over 100 m (Chari, 1980; Prasad and Chari, 1986; King et al., 2009). The initial contact between ice masses and the seabed typically results in continual scouring of the seabed for several kilometers with a preferred orientation (Woodworth-Lynas and Guigné, 1990; Héquette et al., 1995; Wadhams, 2000), or, in other instances, alternately impacting and rotating free of the seabed (Bass and Woodworth-Lynas, 1988), producing a series of craters.

First observed over a century ago (see e.g. Milne, 1876), seabed scouring continues to affect one-third of the world's coastlines (Smale et al., 2008), with scouring rates as high as 8.2 events km^{-1} year^{-1} (Lach, 1996). The depths of the gouge marks observed during early sonar scans of the Canadian Beaufort Sea Wadhams (2000) were on average 2.5 m with maximum recorded gouge depths of 4.5 m. A more recent study of the Canadian Beaufort Sea reported gouges with average depths of 0.3 m (Héquette et al., 1995), while in another (King et al., 2009), the statistical averaging of data collected during a mapping survey conducted on the Grand Banks in 2004 revealed a mean trench depth of 0.3 m and widths of 31 m. According to these reports, trenches do not frequently exceed 1 m in depth, and gouges with depths exceeding 1 m are considered "extreme events" (Barrette, 2011).

The scouring of the seabed of the Arctic ocean has become of particular interest in the past decade as a recent article by the US Geological Survey (USGS) estimated that the region is home to over 10% of world's undiscovered oil reserves, and 30% of world's untapped natural gas reserves (Gautier et al., 2009). Recovery of the oil and gas from reserves that lie beneath the sea requires construction of marine pipes which will be partly submerged beneath the sea surface with long spans supported on the seabed. Exposure of the pipes to the environment leads to both man-made and geo-environmental hazards such as dragging of anchors and cables, thermal buckling, strudel scouring of seabed, and scouring by ice masses.

In Arctic regions, seabed gouging by ice features is generally accepted to pose the most significant risk to buried structures such as offshore gas and oil pipes (Barrette, 2011). The magnitude of the resultant forces due to plowing of the seabed by ice masses in an established scouring process is estimated to be 1000–10,000 tons (Palmer et al., 1990), making marine pipes vulnerable to severe damage if they are to come in contact with the ice masses. The

---

* Corresponding author. Tel.: +1 5129835453.
E-mail addresses: fadaifard@utexas.edu (H. Fadaifard), yannis@mail.utexas.edu (J.L. Tassoulas).

http://dx.doi.org/10.1016/j.ijsolstr.2014.06.013
0020-7683/© 2014 Elsevier Ltd. All rights reserved.

burial of the marine pipes within the seabed is deemed to provide the ideal amount of protection against coming in contact with foreign objects (Palmer and King, 2008).

Although evidence of scouring was first observed over four decades ago, there is limited amount of information available on the active scouring process in the open literature. The ice scouring experiments performed in laboratory settings by Chari (1979) and Barker and Timco (2002) and the in situ ice-ridge scour by Liferov and Hyland (2004) are some of the few well-documented and publicly available information on active scouring processes.

A much sought-after quantity of interest in the design of marine pipes is the optimum burial depth that maximizes safety while minimizing the associated installation and maintenance costs. A deterministic approach through numerical modeling of the seabed scour problem may be used for determining safety of a pipe during a scouring event. This type of numerical simulation can ultimately be used for finding optimum burial depths of pipes for given soil types and scouring events.

Early efforts towards studying and gaining insight into the scouring process by ice masses have resorted to considering basic failure modes and equilibrium of soil and ice ridges (see e.g. Chari, 1979; Palmer et al., 1990). Recently, there has been increased interest in employing advanced numerical methods for investigating this complex phenomenon. Despite the maturity of computational solid mechanics (CSM) and the successfully proven approaches of modeling soil as a porous medium, numerical modeling of complex phenomena such as seabed scouring still faces difficulties. The two predominant difficulties in taking the conventional approach are the interaction of a rigid object, such as an ice-mass, with the soil, and the subsequent large deformation (gouging) induced on and in the soil in the course of such interaction.

The use of arbitrary Lagrangian–Eulerian (ALE) techniques (see e.g. Hirt et al., 1974; Hughes et al., 1981) has been extensively used in the last four decades for solution of free-surface flow problems (see e.g. Souli and Zolesio, 2001; Lo and Young, 2004), fluid–structure interaction (FSI) problems (see e.g. Bazilevs et al., 2008; Wick, 2011), and even in computational solid mechanics involving large deformations (see e.g. Ghosh and Kikuchi, 1991; Rodríguez-Ferran et al., 2002). Within the context of fluid–structure interaction problems, in ALE techniques, the structure is tracked in a Lagrangian fashion, while the fluid computational domain is allowed to deform and warp so that conformity of meshes between the fluid and the object is maintained. Such procedures where a body-fitted mesh discretization evolves with the structure's motion, suffer from the same issues present in Lagrangian tracking of the soil–object interface: in problems where the body is subject to large displacements and rotations, there is still need for computationally intense re-meshing of the domain of interest, and inevitably remapping of variables between meshes.

Previous approaches in numerical modeling of seabed gouging have been generally performed using ALE techniques or remeshing procedures available within commercially available packages such as LS-DYNA (see e.g. Konuk and Gracie, 2004; Konuk and Yu, 2007) and ABAQUS (see e.g. Nobahar, 2005; Nobahar et al., 2007; Peek and Nobahar, 2012). In these works, complex elastoplastic constitutive models are used for the soil. Konuk and Gracie (2004) assumed undrained and isotropic soil response and used the CAP model (Simo et al., 1988) which includes nonlinear kinematic hardening of the soil, while Peek and Nobahar (2012) utilized an elastoplastic material model with the von Mises yield criterion and handled the large deformation using ALE methods combined with re-meshing and re-mapping strategies.

Re-meshing techniques are computationally demanding. In addition to the high computational cost, the regeneration of computational domains requires remapping of variables between a hierarchy of meshes, which may possess the added disadvantage of deterioration, and in extreme cases, lack of convergence to a solution of the nonlinear equations. The contact problem and re-meshing requirements used in classical modeling approaches can be avoided by recasting the soil–object interaction (SOI) as a fluid–object interaction (FOI) problem. The idea of approximating soil behavior as a highly viscous non-Newtonian fluid was successfully tested by Raie and Tassoulas (2009) in numerical modeling of torpedo anchor installations in seabeds using a finite-volume based commercially available computational-fluid-dynamics (CFD) software. The large rigid-body displacement of the torpedo anchor, modeled as a rigid-object, was accommodated using frequent re-meshing of the computational domain.

Other approaches which deviate from classical ones have been proposed for numerical analysis of complex problems subject to large deformations. Sayed and Timco (2009) for instance, utilized the Particle-in-Cell method (PIC) (Harlow, 1964) for flow-like two-dimensional analysis of the large-displacement gouging process.

In this work, we use a simple constitutive model for soil in an attempt to overcome shortcomings of classical methods for analysis of the seabed scour problem. We use a constitutive model that depends solely on the strain-rate of the soil, and re-write the governing equations on a referential domain moving at an arbitrary velocity (ALE representation). The simplifying assumption of history-independent soil behavior allows the computational mesh to be moved independently from the soil particle motion, thereby overcoming mesh distortion issues associated with classical Lagrangian approaches.

We use a mesh-overlapping fictitious domain technique to allow for the arbitrarily large displacements of the ridge that are prescribed. Rather than following the conventional approach of tracking the seabed–ocean interface in a Lagrangian fashion, we adopt an Eulerian approach by describing it implicitly through a level-set function. The ridge-soil contact problem is therefore naturally taken into account by appropriate boundary conditions.

This paper is organized as follows. In Section 2 we summarize soil behavior under scouring, and in Section 3 we present how simple constitutive model may be utilized for approximating soil behavior. The governing equations of the seabed-scour problem and the constitutive model of soil are presented in Section 5. In Section 6 the variational formulation of the governing equations and their discretization are presented. Numerical examples are presented in Section 7.

2. Behavior of soil under scouring

Soon after the recognition of hazards ice features present by gouging, it was assumed that burial of marine pipes such that they do not come in direct contact with ice features is sufficient in preventing damage to the pipes. It was later determined that the soil with close proximity to the ridge undergoes large deformations, making pipes susceptible to damage even in the absence of direct contact. Palmer et al. (1990) qualitatively identified three different modes of behavior for soil under scouring (Fig. 1):

1. Zone I: The region of seabed subjected to plowing by actively coming in contact with ice features is referred to as Zone I. Within this region whose depth is comparable to the scour depth, the soil is subjected to large plastic deformations. Significant upward and downward movement is present within this zone. Upward movement of soil particles is followed by subsequent clearing to the sides of the ridge. Evidence of this mechanism is seen in sonar scans of ocean floors which reveal scour marks with raised shoulders on either side (Prasad and Chari,