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MPM simulations of the interaction between water jet and soil bed

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Abstract

In offshore engineering, pipelines are often buried in the seabed to avoid the damage caused by ocean waves, currents, fishing activities, *etc*. For its reliability, the high-speed water jet has been increasingly used for constructing the pipe trenches. The jet-soil interaction is a highly complicated two-phase problem. A three-dimensional Material Point Method (MPM) model, Anura3D (www.anura3d.com), is used to simulate the jet trenching processes. In this preliminary study, the effect of the water jet speed on the trenching process is simulated. The research demonstrates the advantages of the MPM model in handling the free surface and soil-water interaction problems, and the results are useful for the offshore oil and gas industry. In future research, the different controlling parameters of the trenching operation, including the jet size, water pressure, translational speed and soil strength, will be tested to optimize the trenching operation to achieve high efficiency.

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1. Introduction

The erosion of bed soil with traveling high-speed water jets has wide engineering usage. In offshore oil and gas industry, this technique is often used to construct the trenches on the seabed for burying subsea pipelines. The subsea pipeline is an important part of the oil and gas exploration. It could convey the oil or gas conveniently from the well to the storage and onshore factories. More and more pipelines are being laid on the sea bed. For the purpose of protecting the pipeline from damage of wave impact and fishing trawls, the pipes should be buried beneath the seabed at 1 m – 3 m depth. Most of those trenches are constructed using the jet trencher, for its reliability [1]. The

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mechanism of jet-soil interaction is very complex, so the jet trench depth prediction remains a challenge in the jet trencher design.

The modern mesh-free computational techniques offer new opportunities for predicting the dynamic soil-water interaction problems. In particular, the Material Point Method (MPM) makes use of both discrete Lagrangian interpolation points and Eulerian mesh in the computation [2]. The motion of Lagrangian interpolation points are tracked throughout the computation. Its origin is the Arbitrary Lagrangian-Eulerian method (ALE) [3], the Particle in cell (PIC) method [4], the Fluid Implicit Particle (FLIP) method [5] and the Finite Element Method (FEM) [6]. MPM has many attractive advantages over traditional numerical methods, and is becoming increasingly popular in simulating various solid mechanics problems with large deformation. Firstly, it is convenient to use with history-dependent constitutive models because state variables, such as strain and stress, are carried by material points, which enables the spatial and temporal tracking of these history-dependent variables. Secondly, the use of a background mesh allows for the implementation of boundary conditions in a manner similar to that in FEM, whereas many other mesh-free methods often find it challenging to incorporate the accurate boundary conditions. Many mesh-free methods suffer from unphysical particle clumping or even particle penetration when particles are under tensile stress state, but MPM effectively avoids such tensile instability by retaining the background mesh in the computation [7]. At the beginning of each time step, all the data required for solving the governing equations are mapped from the particles to the neighbouring grid nodes. Then, the weak form of the governing equations is solved at the grid nodes and this solution is used to update the material points. In both FLIP and MPM, the governing equations for the fluid flow are solved on the Eulerian grid and the particle variables are updated in accordance with the grid-based solutions. A key difference of the two methods is that MPM solves the weak formulation of the governing equations, so the MPM is presented in the same framework as FEM. In addition, the constitutive equations are invoked at the material points in MPM whereas in FLIP they are solved at the grid nodes [8].

The current MPM techniques for simulating soil-water interactions generally fall into two categories: one uses a single set of material points [9-11] and the other uses two sets of material points [12-14]. Bandara & Soga [15] and Martinelli [16] gave a detailed literature review concerning different numerical techniques and pointed out the merits and shortcomings of each application. The single particle methods assume similar velocities of the soil skeleton and pore water. In reality, the pore water moves relative to soil skeleton, thus the true water velocity is different from water velocity of the soil material point computed from the formulation with only a single set of material points. It is necessary to consider the motion of the water phase by considering either the true velocity field or relative water velocity with respect to soil skeleton. The paper demonstrates the application of a dual-particle MPM model to the impact of high-speed water jets on the soil bed.

2. Dual-particle MPM model

The two sets of material points represent solid skeleton and water, respectively, and they are allowed to occupy the same location. There are two sets of primary unknowns to be determined. Hence, the behavior of the dry soil, pure water and saturated soil can be modelled in a unified framework. In this formulation, the momentum conservative equations are solved to obtain the acceleration of the solid skeleton and the fluid phase separately. Momentum exchange term (or interaction force) is considered in terms of the drag force. Where water and soil particles coexist in an element, Terzaghi's effective stress concept is adopted for the soil skeleton unless the soil grains are fluidised, in which case the intergranular force becomes zero and the soil particles move under the action of the submerged weight and drag force only.

In the following, the quantities associated to the solid phase and liquid phase are referred with S and W, respectively, in the subscripts. The momentum conservation equations are:

$$(1-n)\rho_S \frac{D\mathbf{u}_S}{Dt} = \nabla \cdot \bar{\boldsymbol{\sigma}}_S + (1-n)\rho_S \mathbf{g} + \mathbf{f}_d \tag{1}$$

$$n\rho_W \frac{D\mathbf{u}_W}{Dt} = \nabla \cdot \bar{\boldsymbol{\sigma}}_W + n\rho_W \mathbf{g} - \mathbf{f}_d \tag{2}$$