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Computational fluid dynamics–discrete element method analysis of the onset of scour around subsea pipelines

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ABSTRACT

In this study, we used a computational fluid dynamics (CFD)–discrete element method (DEM) model to analyze the triggering of sand movement below an offshore pipeline. The advantage of this CFD–DEM model is that it considers the motion and force applied to every individual particle, thereby facilitating detailed simulations of seepage flow and the breakdown of the water–sand mixture beneath the pipeline. The simulation results were similar to previous experimental studies, which showed that scouring occurs after the driving pressure beneath the pipe generates a floating gradient in the sand layer near the wake. Furthermore, the computed critical current velocity that leads to the onset of scour was in reasonable agreement with the observational data. Thus, we consider that CFD–DEM is a promising numerical tool for future investigations of the mechanism that underlies the onset of scour.

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1. Introduction

1.1. Motivation

In offshore engineering, local scour refers to the localized loss of soil around subsea structures due to the acceleration of the flow velocity. When an offshore pipeline is laid on the ocean floor, the amplified fluid velocity around the structure increases its capacity for local sediment transport and this leads to local scour. The stability of a structure will be undermined if a large amount of soil is lost due to scour. The failure of subsea structures due to scour will lead to huge economic losses and disastrous environmental damage. The onset of scour below a pipeline occurs when the burial depth of the pipeline is not sufficiently deep, according to Sumer et al. [1]. However, the mechanism of the onset of scour is still not fully understood because of the lack of quantitative analyses of the movement of sand particles in water flow, which is an urgent requirement during the assessment of subsea pipeline stability.

1.2. Literature review

Many previous studies of local scour focused on scour around the foundations, which are deeply buried in the soil, such as bridge piers. When the foundation of a structure is buried, scour occurs only around the perimeter of the structure. However,

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unlike bridge piers, the foundations of many subsea structures are not deeply buried in offshore oil and gas operations, such as subsea pipelines. If the initial embedding of a pipeline on a seabed is not sufficiently deep relative to the fluid velocity, then the bed may be washed away, thereby leading to the onset of scour. Very few studies have investigated scour under subsea structures [2]. In most cases, local experience is utilized as the best guide for scour prediction, and thus an operating strategy for monitoring and remediation is considered to be necessary [3].

Studies of scour start by determining the threshold fluid velocity that triggers the movements of sediment particles and the resulting sediment transport rate over a flat sediment surface. Sediment particles start to move when the water flow velocity exceeds a critical velocity, which depends on the properties of the sediment. The quantity and the speed of the sediment that moves along the seabed are evaluated based on the sediment transport rates. The interaction between the water flow and the sediment particles is highly nonlinear, so all of the existing formulae used to describe the threshold of motion and sediment transport rates were derived from experimental data. Among the empirical formulae used to calculate the sediment transport rate, the formulae reported in [4–6] are used routinely in numerical models to calculate the bed load sediment transport rate [7–9]. The bed load is defined as the sediment particles that slide and roll along the seabed. Zhao and Teng [10] and Roulund et al. [7] modified the bed load sediment formula to consider the effects of the seabed slope. The suspended load, which is defined as the sediment particles suspended in the water due to turbulence [11,12], is also considered in some numerical scour models. The distribution of the suspended sediment in the water volume is generally predicted by solving the convection–diffusion equation of the concentration of the sediment in the water.

Due to its importance in engineering, scour below subsea pipelines has also been studied extensively in recent decades. Experimental and numerical studies of the scour below pipelines in a steady current have shown that the fluid velocity amplification below a pipeline and the vortex shedding in the wake of the pipeline are the main mechanisms responsible for scour [13–16]. The onset of scour has been studied for a partially buried pipeline and empirical formulae were derived for determining the onset conditions. Chew [17] and Sumer et al. [1] reported that scouring due to the hydraulic gradient below the pipeline is the primary cause of the onset of scour. Sumer et al. found that the critical velocity for the onset of scour increases as the initial burial depth of the pipeline increases. Based on numerical simulations, Zang et al. [2] derived an empirical formula for determining the onset condition in currents and waves.

In previous studies, improvements have been made in the prediction of local scour around subsea pipelines, but the existing methods are highly dependent on empirical formulations to predict the motion of sand in water. However, the mechanisms of water–sand interaction and the collision/friction between sand particles in the water flow were not addressed in previous studies, but they are believed to be key factors that trigger the motion of sediment particles.

1.3. Research aims

In this study, we propose a computational fluid dynamics (CFD)–discrete element method (DEM) model for simulating the interaction between sand particles and water flow around subsea pipelines, and for analyzing the onset condition of local scour for a partially buried pipeline. We also discuss the advantages/constraints of the CFD–DEM model during the investigation of the mechanism of water–sand interaction around sub-sea structures.

2. CFD–DEM model

CFD–DEM is accepted as an advanced computational method in many research areas, such as Aeolian sand movement [17,18], fluidized beds [19], and pneumatic conveying [20]. The reliability of the proposed CFD–DEM model was validated in previous studies, which focused on the motion of sand particles in a wind field, where the research aim was similar to that in the current study [17]. In general, the CFD–DEM model developed in this study comprises three parts, as follows.

- Continuous phase calculation of the water flow, where the conventional CFD method is employed to simulate the water momentum, volume fraction, and energy of water.
- Particle phase calculation of sand motion, where the Lagrange method is used to track and record every particle's trajectory and velocity, as well as the drag force caused by water flow.
- Particle collision model to simulate the collisions between particles during sediment transport. In CFD–DEM, the collision module is used to calculate and record the collision force.

Detailed formulations of CFD–DEM are given as follows.

2.1. Equations of water flow

The continuity and momentum equations of the incompressible water phase in a mixture of fluid and sand particles are as follows:

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla \cdot (\alpha_f \rho_f \mathbf{u}_f) = 0, \tag{1}$$

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