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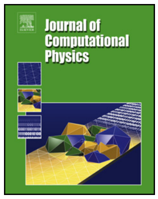

Modelling local scour near structures with combined mesh movement and mesh optimisation

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This paper develops a new implementation coupling optimisation-based anisotropic mesh adaptivity algorithms to a moving mesh numerical scour model, considering both turbulent suspended and bedload sediment transport. The significant flexibility over mesh structure and resolution, in space and time, that the coupling of these approaches provides makes this framework highly suitable for resolving individual marine structure scales with larger scale ocean dynamics. The use of mesh optimisation addresses the issue of poor mesh quality and/or inappropriate resolution that have compromised existing modelling approaches that apply mesh movement strategies alone, especially in the case of extreme scour. Discontinuous Galerkin finite element-based discretisation methods and a Reynolds Averaged Navier–Stokes-based turbulent modelling approach are used for the hydrodynamic fluid flow. In this work the model is verified in two dimensions for current-dominated scour near a horizontal pipeline. Combined adaptive mesh movement and anisotropic mesh optimisation is found to maintain both the quality and validity of the mesh in response to morphological bed evolution changes, even in the case where it is severely constrained by nearby structures.

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1. Introduction

A variety of mathematical and computational models of scour around hydraulic structures, such as offshore pipelines or wind turbine foundations, have been developed over recent years. These seek to describe the coupling between the hydrodynamic and morphological components of the scouring process. Accurate modelling of scour is important since this can lead to the damage and failure of hydraulic and marine structures. Large sums of money are spent in the repair of marine structures as a result of scouring [1]. Hence significant investment is also made in scour protection, guided by predictions of the potential failure mechanisms. Complex numerical models can be used to simulate the (turbulent) flow around the structure, ideally with fully coupled two-way interactions with the morphology of the erodible bed. Seabed morphological models involve a sediment transport description to calculate erosion/accretion processes. An important element of the sediment transport description are formulae for the bedload and suspended transport.

The evolution of the boundary mesh location in response to bed morphodynamics also requires changes to the internal computational mesh. If this is not done, or is not done well, this can lead to poor quality meshes which compromise simulation stability and accuracy. A widely used approach to this problem is to use mesh movement methods to propagate

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the boundary mesh movement into the domain, in an attempt to maintain mesh quality throughout [2,3]. However, in the case of extreme bed movement and/or where this movement is close to a fixed structure in the domain (which inevitably constrains the mesh and its ideal movement to some degree), it is very difficult to maintain mesh quality with mesh movement algorithms alone.

One of the earliest studies to present a holistic dynamic description of the local scour process at submarine pipelines, taking into account both sediment transport contributions (i.e. bedload and suspended transport), was performed by Brørs [4]. In that approach the computational mesh evolved in time in order to represent the moving bed location due to scour under a single pipeline. A structured computational grid was utilised with each node in the domain moved vertically, maintaining a relative spacing. But this type of method can lead to problems with resolution and mesh characteristics (e.g. orthogonality and skewness), especially in the case of large bed deformations [2,4,5]. With unstructured computational grids, it is relatively straightforward to use variable resolution within the domain, but due to arbitrary connectivity and cell shape it is also arguably more complicated to move the mesh nodes on the bed and in the domain interior. Although the development of moving grid techniques has been generally less well studied than other adaptive mesh techniques, there have been a lot of progress in the past decades, such as partial differential equations (PDE)-based and spring-based analogy methods [6]. From the moving mesh PDE-based approaches, the relatively simple Laplacian smoothing has been a common choice to tackle mesh deformation in response to local sediment scour due to its robustness and ease of implementation with an unstructured grid in a complex domain [7]. As we will argue in this paper (section 5), movement of nodes alone may not be sufficient to maintain an adequate mesh resolution and/or structure, especially for cases with extreme bed deformation.

With the wider development of unstructured grid based methods in computational fluid dynamics (CFD), a broad range of techniques for arbitrary resolution specification and updating of the computational mesh are available. The main motivation for these is to impart both resolution and geometric flexibility as well as to optimise computational efficiency: minimising computational cost for a required accuracy, or maximising accuracy for a given cost. Here a further goal is targeted: the use of this range of techniques to maintain an optimal mesh when subjected to external boundary deformation.

Techniques for updating the mesh include those which: (i) perform local topological operations (e.g. sub-dividing elements, or changing mesh connectivity through the swapping of element faces and edges) to change the size, and potentially the shape, of mesh elements (variously termed adaptive mesh refinement (AMR), *h*-adaptivity and mesh optimisation depending on the specifics of the algorithm [8–10]); (ii) methods which continuously move or redistribute the location of mesh vertices while maintaining mesh connectivity (often termed mesh movement or *r*-adaptivity [6]); and (iii) their combination in so-called *hr*-adaptive methods [11].

In this work we present a new mesh optimisation/movement (or *hr*-adaptive) framework for computational morphodynamics. This includes the use of relatively sophisticated mesh movement algorithms to account for the bed evolution, while utilising mesh optimisation methods in order to: maintain mesh quality under extreme and complex scenarios; vary the total degree of freedom count as the problem complexity evolves; and help track solution features in the wider domain. The framework will be demonstrated on a complex scour problem with a hydraulic structure (i.e. pipeline) close to the bed; the closeness being particularly challenging due to the constraints the structure imposes on the mesh movement, and the significant difference in degree of freedom count ideally required in the gap between structure and bed as the scour progresses at different times into the simulation. Scenarios considered include both live-bed (i.e. the approaching flow continuously transports sediment into a local scour hole) and clear-water (i.e. the approaching flow is clear and does not contain sediment) conditions. Results are benchmarked against laboratory data and prior numerical studies which also considered the same test case. This paper represents a significant extension and improvement over our previous paper [12] which reported on the initial steps in this work.

The remainder of this paper is organized as follows. In section 2, we review the governing mathematical equations which are relevant for the physics of local scour and turbulent flows. In section 3, we present control volume/finite element-based numerical discretisation algorithms for solving coupled computational fluid dynamics with sediment conservation laws. Section 4 describes the adaptivity algorithms we employ, including mesh movement and optimisation-based anisotropic mesh adaptivity. Numerical experiments are carried out in section 5, where validation and benchmarking against physical and numerical experiments are considered.

2. Mathematical equations

This section presents the mathematical formulation for the flow field model and the scour model including the sediment transport equations.

2.1. Flow model

The approach taken here for the hydrodynamics is to consider the single phase solution of the incompressible Reynolds-averaged Navier–Stokes (RANS) equations under the Boussinesq buoyancy approximation. This comprises the continuity equation (incompressibility condition)

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

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