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Numerical modelling of the erosion and deposition of sand inside a filter layer

Niels G. Jacobsen[a,*], Marcel R.A. van Gent[a], Jørgen Fredsøe[b]

[a] Coastal Structures and Waves, Deltares, The Netherlands
[b] Department of Mechanical Engineering, Technical University of Denmark, Denmark

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ABSTRACT

This paper treats the numerical modelling of the behaviour of a sand core covered by rocks and exposed to waves. The associated displacement of the rock is also studied. A design that allows for erosion and deposition of the sand core beneath a rock layer in a coastal structure requires an accurate prediction method to assure that the amount of erosion remains within acceptable limits. This work presents a numerical model that is capable of describing the erosion and deposition patterns inside of an open filter of rock on top of sand. The hydraulic loading is that of incident irregular waves and the open filters are surface piercing. Due to the few experimental data sets on sediment transport inside of rock layers, a sediment transport formulation has been proposed based on a matching between the numerical model and experimental data on the profile deformation inside an open filter. The rock layer on top of a sand core introduces a correction term in the Exner equation (the continuity equation for sediment and change in bed level). The correction term originates from the fact that the sand can only be deposited in the pores of the filter material.

The numerical model is validated against additional data sets on the erosion and deposition patterns inside of an open filter. A few cases are defined to study the effect of the sinking of the filter into the erosion hole. The numerical model is also applied to several application cases. The response of the core material (sand) to changes in the wave period and wave height is considered. The effect of different layouts of the filter is studied in order to investigate the effect of different filter profiles on the resulting erosion. Finally, it is studied how much the design of a hydraulically closed filter can be relaxed to obtain a reduction in the design requirements of the filter thickness, while the deformation to the sand core remains acceptably small.

1. Introduction

Rock filters are commonly used in the design of coastal structures and scour protection to prevent erosion of the underlying material either by internal transport processes at the interface or by suction removal. The traditional design approach is to avoid any type of erosion. One such approach is the geometrically tight filter design, where a number of filter layers are placed on top of each other in such a way that the grains in the finer layer cannot pass through the pores of the coarser, adjacent layer due to geometrical constraints. This type of filter design is expensive and difficult to install, because it typically consists of a large number of layers.

One alternative approach is to use fewer layers, where the material is not geometrically constraint to pass through the pore structure of the coarser layers. The adopted approach to suppress any sediment motion in the sandy bed is to increase the filter layer thickness to such a degree that the hydraulic loading at the rock-sand interface is smaller than the threshold for mobilisation of the sediment [1]. This type of filter design is termed hydraulically closed filters. The hydraulically closed filter is easy to install, but the consumption of the filter material is still considerable. The design of hydraulically closed filters relies on experimental data for the initiation of motion of sediment grains at the interface. Data for unidirectional flow [21,36] and for oscillatory flow and real waves [21,5] are available. Furthermore, Bakker et al. [1] approach the stability of the sandy base under an armour and a filter layer (hydraulically closed) from a theoretical point of view and they found that large ratios between base and filter materials can lead to a more stable bed than a small ratio. Klein Breteler et al. [21] specified the incipient motion in terms of the critical hydraulic gradient inside the granular filter, while Dixen et al. [5] defined the initiation of suction of the base material as a function of the critical mobility number, where the applied velocity was measured outside of the armour blocks.

The present work is concerned with the concept of open filters (see *e.g.* the experimental works by [40]and Fig. 1), where the hydraulic loading at the interface between the filter and the base material (sand) is large enough to mobilise the sediment at the interface between the

* Corresponding author.

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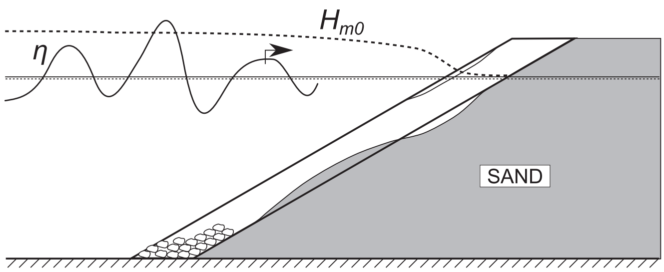

Fig. 1. An example of the erosion and deposition pattern in an open filter under irregular wave loading. H_{m0} is the spectral wave height and η the instantaneous surface elevation.

base and the filter. The sand at the core is not subject to any geometrical constraints, consequently, the sand profile is deformed with time. Van Gent and Wolters [40] presented the results from an experimental campaign, where the main focus was on the response of the sand profile as a function of the material properties of the filter and the hydraulic loading. Their investigation did not include variations in water level and the variation in the wave steepness was limited.

The present work presents a newly developed numerical model, which is calibrated with and validated against the experimental data from Van Gent and Wolters [40]. This model is used to study the effects like variations in the layout of the filter and changes in water level. Van Gent et al. [41] observed that the hydraulic gradient along the rock-sand interface depends on the wave steepness, why it is expected that the wave steepness (wave period) must affect the erosion and deposition patterns as well; this dependency is analysed in the present work.

One of the model requirements is a numerical model that is capable of simulating wave breaking and porous media flow. The first VOF-model that solved the Navier-Stokes equations for the free-surface flow in- and outside of permeable coastal structures was presented by Van Gent et al. [38] and they showed that this approach can provide valuable insight into the physical processes. Several other VOF models have since been developed for the interaction between waves and permeable structures [20,23,25,32,11]. Jacobsen et al. [17] demonstrated that the version of the Navier-Stokes equations by Jensen et al. [20], which includes the interaction with permeable coastal structures, works successfully for breakwaters. The implementation by Jensen et al. [20] will be adopted in the present work.

Morphological modelling with detailed CFD models has also been carried out in both river and coastal problem over the last couple of decades, but the effect of a free surface on the morphodynamics [10,24,28,34,14] is not yet included on a regular basis. Morphological modelling including free surfaces is time consuming, because there is a large difference between the time scale for morphological equilibrium and quasi-steady hydrodynamics. This means that the simulation time typically exceeds the time it takes to reach quasi-steady hydrodynamic conditions and the intra-wave motion must still be resolved: the combination of these requirements results in a huge number of computational time steps. This problem was addressed by *e.g.* Stahlmann [34], who used a snap-shot of the hydrodynamic loading to calculate the development of a scour hole around a tripod structure over many wave periods. Subsequently, the hydrodynamics was re-calculated over the new profile of the bed and a new snap-shot of the hydrodynamics was used to evaluate the scour development. An alternative is to use the standard approach of morphological acceleration. The latter will be adopted in this work, since the hydrodynamic forcing is that of irregular waves, where the definition of a representative regular forcing (if it exists) is a research topic in itself.

As seen from the above descriptions, neither the modelling of the interaction between permeable structure and waves nor the modelling of sediment transport and the resulting bed deformation due to waves are new research areas. The combination of these two branches, on the other hand, is to the authors' knowledge not attempted before.

The present work is organised as follows: The numerical model is presented in Section 2 and the calibration of a sediment transport formula is presented in Section 3, where the validation of the numerical model is also presented. In Section 4, the numerical model is applied to different configurations of the open filters, the effect of wave heights and periods are investigated and a less strict formulation of a hydraulically closed design rule is analysed. The work is finalised with a conclusion.

2. Mathematical model

The mathematical model is described in this section. The numerical framework is OpenFoam [43] version foam-extend-3.1 and the framework provides the means of solving free surface flows with the volume of fluid method (VOF). Based on the discussion in Section 1, the following requirements are specified to the numerical model: (i) Solution to the Navier-Stokes equations in- and outside of a permeable layer, (ii) tracking of the free surface in- and outside of a permeable layer, (iii) generation and absorption of free surface waves and (iv) modelling of sediment transport and the resulting change in bed level inside an open filter. Each of these components is addressed below.

2.1. Hydrodynamic model

Jensen et al. [20] presented a form of the Navier-Stokes equations that accounts for the presence of permeable, coastal structures. This model has been successfully used to describe the interaction between waves and permeable coastal structures such as breakwaters [17] and to validate the wave-induced pressures inside an open filter [41]. Jensen et al. [20] described the Navier-Stokes equations in terms of the filter velocity, and the Navier-Stokes equations took the following form:

$$(1 + C_m)\frac{\partial}{\partial t}\frac{\rho \mathbf{u}}{n_p} + \frac{1}{n_p}\nabla\cdot\frac{\rho}{n_p}\mathbf{u}\mathbf{u}^T = -\nabla p^* + \mathbf{g}\cdot\mathbf{x}\nabla\rho + \frac{1}{n_p}\nabla\cdot\Gamma_u\nabla\mathbf{u} - \mathbf{F}_p \tag{1}$$

Here, C_m is the added mass coefficient, t is time, ρ is the density of the fluid, $\boldsymbol{u}$ is the filter velocity vector, n_p is the porosity of the permeable structure, p^* is an excess pressure, $\boldsymbol{g}$ is the vector due to the acceleration of gravity, $\boldsymbol{x}$ is the Cartesian coordinate vector, Γ_u is the diffusivity of the velocity field and $\boldsymbol{F}_p$ is the resistance force due to the permeable structure. The system of equations is closed with the incompressible form of the continuity equation:

$$\nabla\cdot\mathbf{u} = 0 \tag{2}$$

The tracking of the free surface is performed with the advection algorithm termed MULES, which is the standard method available in OpenFoam. The advection equation takes the following form:

$$\frac{\partial F}{\partial t} + \frac{1}{n_p}[\nabla\cdot\mathbf{u}F + \nabla\cdot\mathbf{u}_r(1-F)F] = 0 \tag{3}$$

Here, F is the indicator function of the VOF-field and $\boldsymbol{u}_r$ is a relative velocity introduced to keep a sharp interface, see Rusche [31] and Berberovic et al. [2] for details. Note the factor $1/n_p$ that was introduced by Jensen et al. [20] to ensure the conservation of mass, when the fluid passes through a permeable structure. This correction term is required, because the water/air can only occupy the pore volume in the permeable structure.

The indicator function is also applied to evaluate the spatial variation of the density and the viscosity:

$$\rho = F\rho_1 + (1-F)\rho_0 \quad \text{and} \quad \Gamma_u = F\Gamma_{u,1} + (1-F)\Gamma_{u,0} \tag{4}$$

Here, the sub-indices refer to the fluid properties for $F = 0$ and $F = 1$. In this work, $F = 1$ means that the computational cell is filled with water and $F = 0$ means that the computational cell is filled with air. Any cell with a value of F between 0 and 1 will be located at or close to the free surface.