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Towards a general prediction-model for the current-induced mobilisation of objects on the sea floor

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ABSTRACT

The aim of this work was to quantify the physical conditions, required for the mobilisation of unexploded ordnance devices (UXO) on the sea floor. As a basis for this, the hydrodynamic processes around UXO were measured in the wind tunnel and the flume tank in terms of conditions, especially Reynolds numbers. From these experiments, the typical shape of a sandy sea floor in the close vicinity of an object, due to current-induced burial was determined. Knowing this, the model for current-induced mobilisation of objects was developed. The model assumes a critical dimensionless Moment Factor $MF = a \cdot Re^b$, where the parameters a and b had to be investigated. This was accomplished by performing a total number of 287 numerical simulations, wind-tunnel testings and flume tank experiments at different geometric scale factors (1:10, 1:5, 1:2 and 1:1). With the parameter values so determined, the model describes the critical situation of an arbitrary shaped cylinder-like object regarding the incident flow velocity, the immersed mass and the burial depth, as well as the length and the volume-averaged diameter of the object.

1. Introduction

In many sea areas numerous unexploded ordnance devices (UXO) from previous wars contaminate sea floor. They can be found buried in and on the sea bed. These objects represent a major risk for life and equipment for all marine activities touching the sea bed such as fishery, offshore installation effort, mining and naval activities. Particularly, the routes for subsea cables and pipelines are recommended to be surveyed and cleared of potentially dangerous objects prior to any installation effort to establish a safe working environment. Since the number of potential objects to be investigated is unknown, time and cost for these campaigns cannot be quantified accurately. This uncertainty can delay the subsequent installation effort and therefore, increases the overall project risk. This also applies for repair and maintenance activities, as a route is assumed to be free of UXO only for a limited amount of time. Therefore, a good knowledge about the physical requirements for the initial mobilisation of objects on the sea floor is needed to decide whether a previously cleared corridor can be assumed to be unchanged. In this paper, the requirements to mobilise UXO on the sea floor by currents are thus quantified. This approach moves away from a temporal sign off to a physical, event driven, and quantifiable approach by understanding and describing the processes that make objects migrate on the sea floor.

According to (Wilkens and Richardson, 2007), cylindrical objects, bedded on a sandy sea floor, can be buried or partially buried by a series of different processes. The burial process depends on a large number of variables as shown in (Jenkins et al., 2007). Within this context we distinguish between processes in the close vicinity of the object and those that also occur in the far field. According to (Catano-Lopera et al., 2007), (Jenkins et al., 2007) and (Wilkens and Richardson, 2007), the far field processes like the bottom slope and the change due to dunes and ripples, as well as the change of the structure of the seabed, are independent of the presence of objects on the sea floor. In contrast to this, the near-field processes depend on the presence of an object itself and variations in the fluid flow around it. In particular the erosion of sediment, the formation of scour and the accumulation of sediment depend on a large number of different parameters and boundary conditions, which was described in (Wilkens and Richardson, 2007), (Jenkins et al., 2007), (Shields, 1936) and (Guyonic et al., 2007). A model for the self burial of small objects was published in (Whitehouse, 1998), which gives the burial depth of a cylinder of unknown size by time. This model, however, requires the knowledge of the maximum burial depth due to scour-induced self-burial, which is also given in (Whitehouse, 1998). The maximum burial depths for small

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objects with diameters of up to $D = 10.5\,cm$ and lengths of up to $L = 32\,cm$ can be found in (Rennie et al., 2017). A description of the physical processes for scour-induced self-burial of a cylindrical object on a sandy sea floor will be given in Section 3.1. Here, a fully developed interaction between the object, its environment and the fluid is found.

Extensive investigations on the self-burial and the mobilisation of small objects on the sea floor have been examined during the *Strategic Environmental Research and Development Program* (SERDP). Models for the mobilisation of UXO have already been published in (Rennie et al., 2017) for small objects in accelerating currents. They assume a relatively small object size, and thus may not necessarily be applied to larger objects. Besides this, several models for the mobilisation of different objects on the sea floor were published, by e.g., (Wiberg and Smith, 1985), (Nott, 1997), (Nandasena and Tanaka, 2013) and (Noormets et al., 2004).

In contrast to the existing approaches that are restricted to small ranges of sizes and incident velocities, in this study a general model was developed. The mobilisation is described by a force balance model. As the driving hydrodynamic loads can be scaled by the dimensionless Reynolds number, this was used to scale the objects sizes and the incident velocities. Thus, the model was calibrated by experiments and numerical simulations within a range of 4 orders of magnitude of the Reynolds number. The model is therefore applicable at least within this range. Furthermore, the exact shape of the individual object does not have to be known. The general model requires only a few characteristic measures like the length, the average diameter and the weight of the object. Consequently, this approach is useful in a very wide range of applications and for unfamiliar objects.

2. Methods

The transferability of the results from experimental analysis on small scale models to full scale is subject to numerous uncertainties. With respect to this, the conceptional preparation of the relevant laboratory tests is a considerable scientific challenge. The choice of geometric, kinematic and dynamic parameters of the down scaled model, the sediment and the fluid flow plays a decisive role. For the vortex- and turbulence structures as well as for the characteristics of the wake of an object and the separation of the flow, which all affect force-loads on the object, the Reynolds-number

$$Re = \frac{UD}{\nu} \tag{1}$$

with the incident velocity U, the characteristic length scale D and the kinematic viscosity of the fluid ν is the relevant dimensionless number. For the initiation of sediment transport, the particle-Froude number

$$Fr_p = \frac{U}{\sqrt{\frac{\rho_p - \rho_w}{\rho_w} g d_p}} \tag{2}$$

and the Shields Parameter

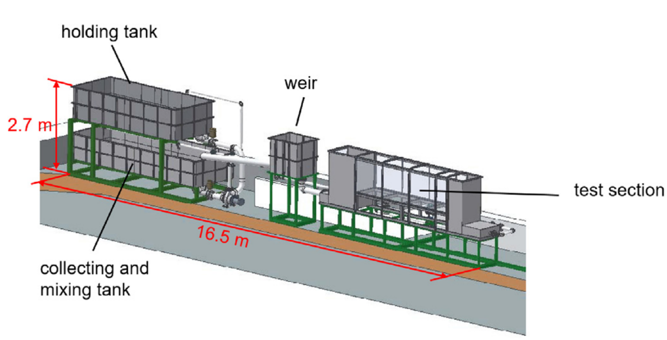

Fig. 1. The water-channel at the University of Rostock.

$$Sh = \frac{\tau_w}{(\rho_p - \rho_w) g d_p}, \tag{3}$$

defined by (Shields, 1936), with the densities of water ρ_w and the particle ρ_p, the particle diameter d_p, the gravitational acceleration g and the wall shear stress τ_w are the relevant numbers. The critical Shields Parameter Sh_c is defined by the initial movement of the individual sediment. From their definitions it is obvious that these numbers cannot all be conserved at the same time when scaling an object. Due to this, it is necessary to prove that the results from the scaled water flume experiments can be transferred to the ocean. The concept for this was to guarantee that the scaling of the sediment transport continues to be done by Sh and Fr_p even though the Reynolds number is much higher in the ocean than in the flume experiments.

Extensive Measurements of the ruling vortex structures like the horseshoe vortex and the recirculation vortex, whose horizontal length again is a good measure for the separation at the object, have been done in the water flume and in the wind-tunnel. The measurements in the wind-tunnel were conducted at the same Reynolds numbers as it can be found in the ocean.

2.1. Experimental facilities and techniques

The near-scale scour and mobilisation experiments were carried out in the flumetank of the University of Rostock and for larger scale in the *Fast Flow Facility* (FFF) at HR Wallingford.[1] The goal was to determine the maximum burial depth of the objects, the scour pattern due to a constant incident flow and the mobilisation velocities for objects at different burial depths. A schematic of the channel at the University of Rostock is shown in Fig. 1.

The sediment grain size was $0.1\,mm < d_p < 0.3\,mm$ with a grain density of about $\rho_p = 2600\,kg/m^3$ in all flume tank experiments. To observe the development of scour and burial of the objects, images of the scenario with a temporal resolution of 5 s were recorded. For further investigation, different optical and laser-optical measuring systems like the Particle Image Velocimetry (PIV), the Laser Doppler Anemometry (LDA) and a Plenoptic Camera were used. Via these systems, the 3-dimensional 3-component velocity fields as well as the surface structure were measured.

Experiments in a Göttingen-Type wind-tunnel were performed to determine the flow-induced loads on the objects with a 6-component balance. By conserving Re, these loads can be converted to real scale, using the drag coefficient c_D and the lift coefficient c_L. In addition to these studies, real scale experiments were performed in the FFF of HR Wallingford. More detailed information on the FFF are given in (Whitehouse et al., 2014). While the fluid velocity fields for the University of Rostock experiments were measured with PIV, LDA and Hotwire Constant Temperature Anemometry (CTA) in the wind-tunnel, acoustical systems were used in Wallingford. A downward looking Aquadopp[2] measured the incident velocity profile, whereas two Vectrino II[32] were placed close to the objects to register the turbulence.

2.2. Model for current-induced mobilisation

A first approach for the current-induced mobilisation model was shown in (Menzel et al., 2017). The basic equations will also be shown here for a better understanding of the newest approach. The basic idea is that objects on the sea floor become partially buried (see section 1). In (Menzel et al., 2012) it was shown that cylindrical objects tend to orientate with their cylinder axis normal to the mean incident velocity direction due to the Munk-moment. Due to this, the basic approach of the current-induced mobilisation model is that the object has to be

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