Mine Burial by Local Scour and Sand Waves

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LONG-TERM GOALS

Our long-term goal is to help advance the U.S. Navy's capabilities for Mine Burial Prediction (MBP) by conducting large-scale laboratory observations that will both improve our knowledge of the physical processes involved in mine burial and provide a vital bridge between field experiments and numerical modeling of mine burial processes in shallow waters.

OBJECTIVES

The main objective of this effort over the past years has been the direct observation and monitoring of the burial process of various cobbles (model mines) induced by waves and the combined action of waves and currents. The experimental conditions have made it possible to observe the burial process due to both local scour around the mines as well as the passage of large sand waves. More recently, these rather unique observations, in addition to bathymetry and velocity measurements, are being used to test, validate, and calibrate numerical model predictions generated in *FLOW-3D*. Our aim by

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coupling the two approaches is to provide a more comprehensive study that focuses on turbulent intensities, characterization of horse vortex, and vortex shedding mechanisms which are of significant importance to the erosion, transport and deposition of sediment in the vicinity of the object. Ultimately, this work will aid in the development of a mechanistic model for Mine-Fluid-Sediment (MFS) interaction by the ONR Mine Burial Prediction Team.

APPROACH

The research effort is composed of detailed laboratory measurements coupled along with numerical simulations (using *FLOW-3D*) to better understand the flow structure around partially buried objects. While previous studies have focused on flow structure and/or scour around objects, e.g., Sumer et al., (2003), Smith and Foster (2005), and Testik et al. (2005), have let to important contributions, all made simpling cases in which either the object was fixed and the bed could scour around it or the flow was measured around an object resting on a flat bed. Prior to this work no extensive experimental, nor numerical, investigations have been dedicated to the examination of velocity measurements around a partially buried 3D object in a deformed movable bed. Thus, the experimental work discussed herein focuses on the case of steady flows to gain significant insights to the flow/burial processes before moving toward the more complex case of oscillatory flows.

Our primary research team consists of the PI, Marcelo H. García and Co-PIs, Yovanni A. Cataño-Lopera (research associate), and Blake J. Landry (PhD student).

WORK COMPLETED

Processing of the data from the laboratory experiments was completed. Experiments were conducted in a multipurpose wave-current flume having dimensions of 49 m x 1.8 m x 1.2 m with the middle 24 meters of the flume containing a 30 cm deep sand bed test section. Tank flow conditions where conducted with a mean flow velocity of 20 cm/s with a water depth of 40 cm. Prior to each experiment the sand bed was leveled and model mine was placed on top of movable sediment bed. The dimensions of the model mines employed were as follows: cylindrical mine having a diameter = 10 cm, length = 20 cm, and specific gravity = 2.3; and manta mine having top diameter = 10 cm, height = 20 cm, bottom diameter = 20 cm, and specific gravity = 2.0. The same flow conditions were imposed for both the finite-length cylindrical and truncated-cone shaped objects which served as representative models for cylindrical and manta mines, respectively. Laboratory experiments utilized acoustic and optical methods to provide detailed measurements to obtain both qualitative and quantitative evidence to better understand the flow structures that are key in the burial process. After the object reached its burial equilibrium depth a fine resolution scan (i.e., Δx = 1 cm and Δy = 0.5 cm) of the bed in the vicinity of the object was conducted using a Keyence laser displacement sensor having a vertical resolution of 0.5 μm. Detailed records of the flow characteristics were acquired throughout the experiments by nearly 70 velocity profile measurements using an ADV at densely spaced discrete points (i.e., 13 points vertically spaced at $\Delta \ln(z) = 0.25$ starting at 1.75 cm from the sand bed over one lateral half of each mine). Refer to Figure 1 for velocity measurement locations which are superimposed over the bathymetry acquired from the laser scans.

In addition, numerical simulations using *FLOW-3D* were performed for the various laboratory experiments under uniform flow conditions. Computations were performed on a PC having 2.6 GHz dual-core processor, 8 GB of RAM and running Microsoft Windows Vista 64-bit platform. Model results from two different turbulent closure schemes (i.e., κ-ε and LES) were used to determine the mean and unsteady flow field around both model objects (Figure 2) which are compared against the laboratory cases. Also, to explore the effect of turbulence, turbulent kinetic energy (TKE) was compared between simulation and lab results (Figure 3) as well as computation of vorticity intensities (Figure 4).

RESULTS

Based on the detailed bed measurements at equilibrium scour conditions as well as the FLOW-3D computational models, various insights to the burial process have been made. In the case of unidirectional flows, as shown here, aside from the development of a horseshoe-shaped scour hole around the upstream face of objects through erosion, a unique sediment deposition feature occurs along the center line of the both objects (i.e., short-cylinder and truncated cone), as seen in Figure 2, formed arguably by the supply of sediment from the horseshoe-shaped scour region. The central ridge extends out roughly twice the length of the short-cylinder and about twice the mean diameter in the case of the truncated cone. This phenomena turns out to be a self-protecting mechanism against further sinking and the initial mounted object-fluid-bed system evolves towards defining a composite object-fluid interaction where the composite object is now the combination of bed plus object.

In addition, laboratory velocities measurements from the flume were used to compute contours of time averaged flow velocities, turbulent intensities, Reynolds normal and shear stresses at different locations in the x-y, x-z, and y-z planes all of which provided supporting evidence for the understanding of the mechanisms involved in the formation of scour and deposition regions around the object. The data showed that mean velocities are strongly affected by the object and regions of high acceleration occur at the sides, and back and front of the object, respectively. This is responsible for high erosion rates resulting in significant scour formation and subsequent sinking of the object. Main flow acceleration and decelerations occurred on top of the object (+20%) and along centerline, just downstream of the object (-90%), respectively. Furthermore, results showed velocities turn negative inside the recirculation zone in the scour depression formed upstream the object, while, low and negative velocities are also present over the ridge downstream of the mine. In the cylinder case, a scour gap develops which limits the development of the ridge region due to strong velocities and vortex shedding over it (i.e, downstream centerline of the object). A recirculation zone forms in the near-downstream region of the object which facilitates the deposition of sediment leading to the formation of a sharp-shaped sand ridge.

Regarding the numerical simulations, good agreement was observed between laboratory experiments and simulation. Both tested turbulence closure schemes, κ-ε and LES, show the formation of a pulsating necklace y-vortex upstream of the object which excavates sediment and carries towards the sides with the help of a x-vortex that helps sweeping the sediment in the downstream direction. Formation of z-vortex cores at the sides of the object sweeps sediment towards the centerline which in turns results in the formation of the central ridge in the downstream part of the object. The κ-ε closure reproduced the mean flow structures such as average flow fields of velocity, turbulent kinetic energy, rate of turbulent kinetic energy dissipation, normal and shear stresses, observed in the experiments fairly well. In addition, the length of the recirculation region was found to be in good agreement with the experimental data when using both closure schemes. The simulations also allow visualization of the pulsating vortex shedding from the top of the object (Figure 4). The LES simulations revealed a complex unsteadiness of the flow structure around the object which might play a more significant role in the sediment entrainment process than that exerted by the mean flow characteristics, observed with the κ-ε scheme. Distribution bed shear stresses obtained with both turbulence models show that peak values are of much higher intensities than mean values. This leads to consider that any prospective numerical burial model should take into account the significant impact of the unsteadiness of the flow field, as given by LES, rather than its mere mean structure as given by κ-ε.

IMPACT/APPLICATIONS

The results of this study show the significant importance of not only the mean flow characteristics but also the turbulent intensities on the mobility of sediments around the object and that intimately transcends the extent and development of the scour hole around the object. The present findings are hoped to be of great help for the development of mathematical model of the local scour and burial mechanisms of 3D objects, in particular of short cylinders and truncated cones. The applications of the current findings are believed to be helpful for the current effort by ONR's Mine Burial Prediction Program as well as for future military and civilian welfare.

RELATED PROJECTS

Motivated by a slight but noticeable variation in ripple geometric characteristics over the entire length of the wave flume especially under wave reflections of less than 10 % during this experimental effort as well as other previous studies, such as Cataño-Lopera et. al.(2008), Landry and Garcia (2007), and Cataño-Lopera and Garcia (2006), additional work was conducted to further explore and quantify these observations. Please refer to the companion report entitled "Ripple Morphology under Oscillatory Flow" for more information.

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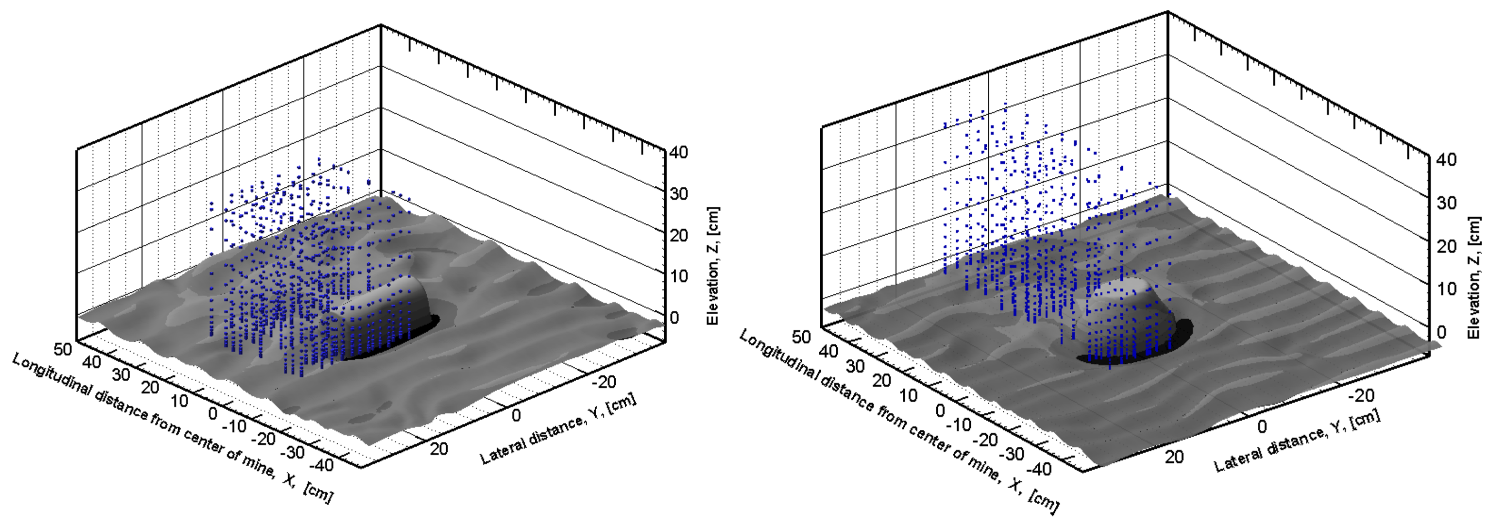


(a) (b)

Figure 1: Location of velocity point measurements for velocity profile around objects (a) cylinder (b) truncated cone

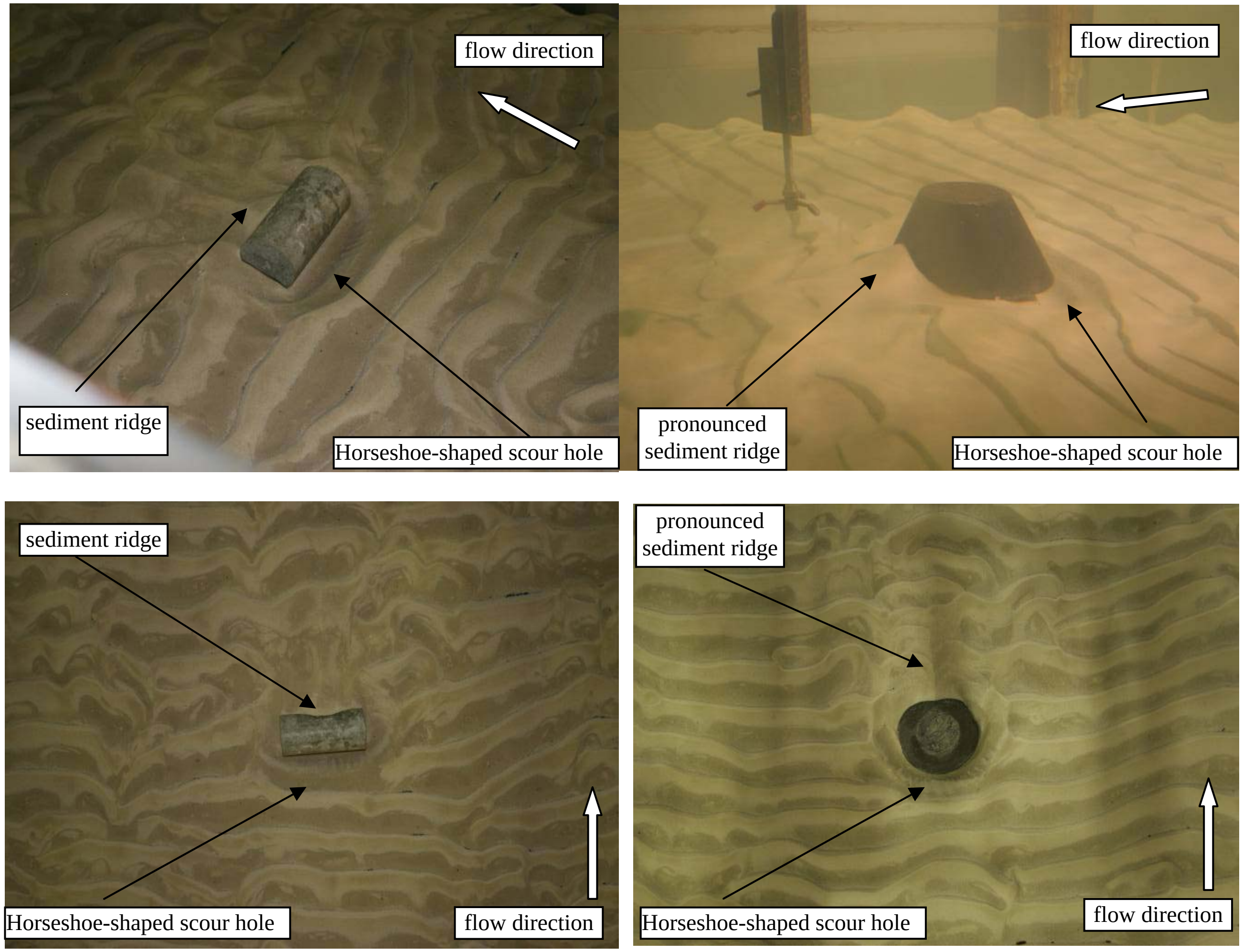


Figure 5: Photographs of sediment ridge and horseshoe-shaped scour regions around the cylindrical and manta mine model in the laboratory flume. Subplots (a) denote side view perspectives while subplots (b) show plan views.

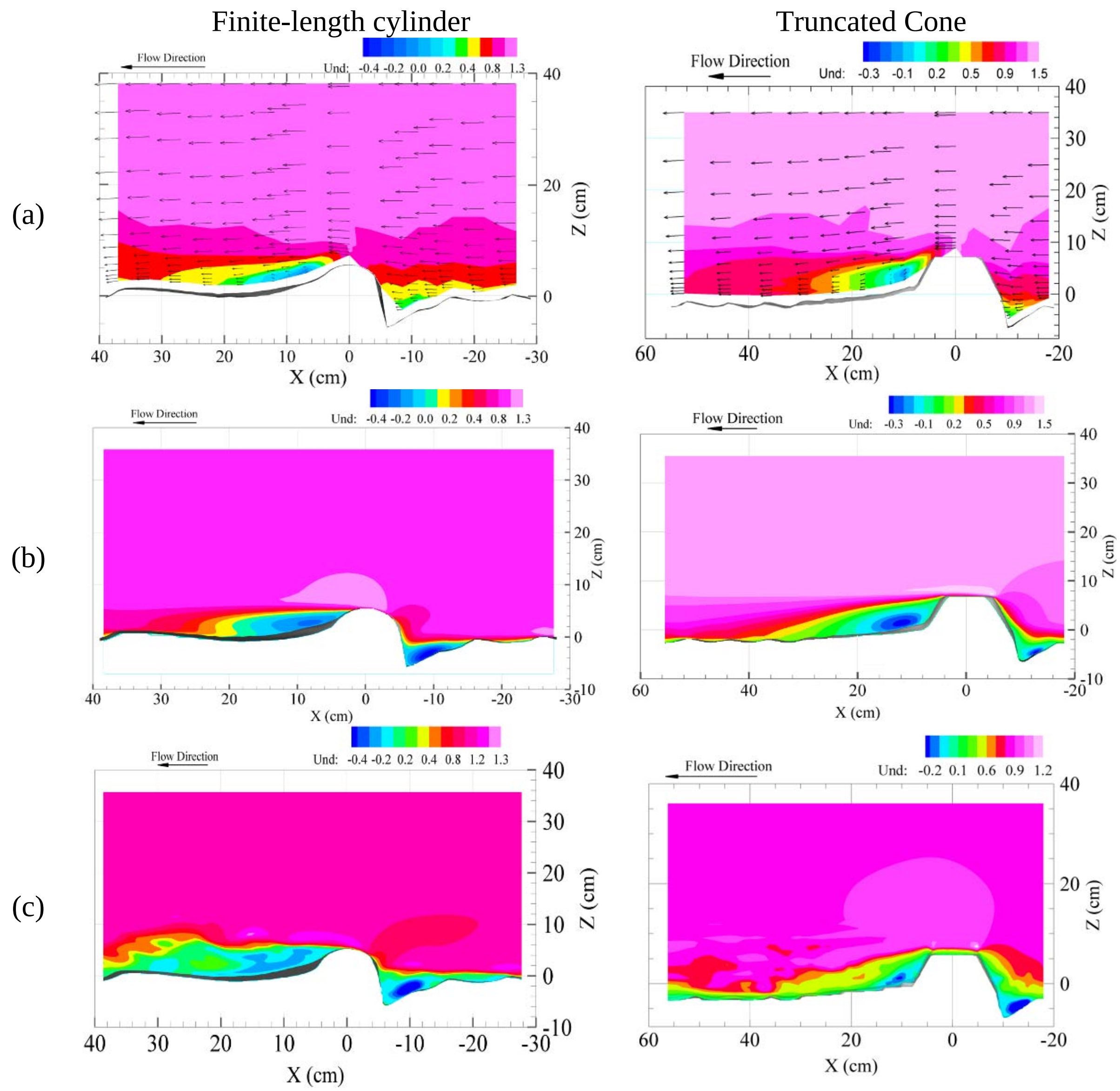
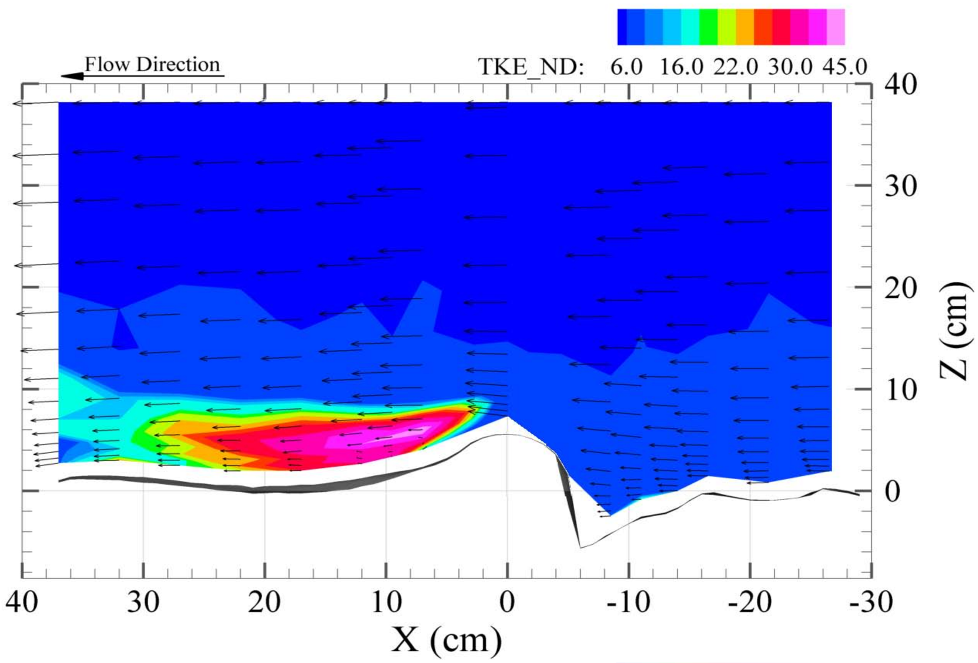


Figure 2: Comparison of mean flow velocities from measured experimental data [subplots (a)] and numerical FLOW-3D simulations using two turbulence closure schemes [subplots (b) κ-ε and (c) LES] for each mine.

(a)



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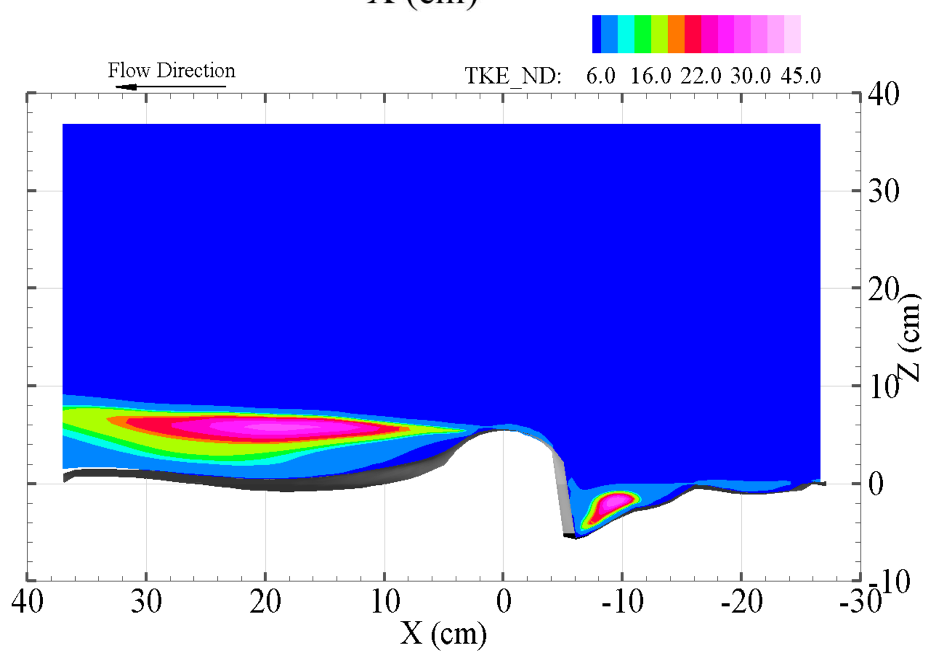
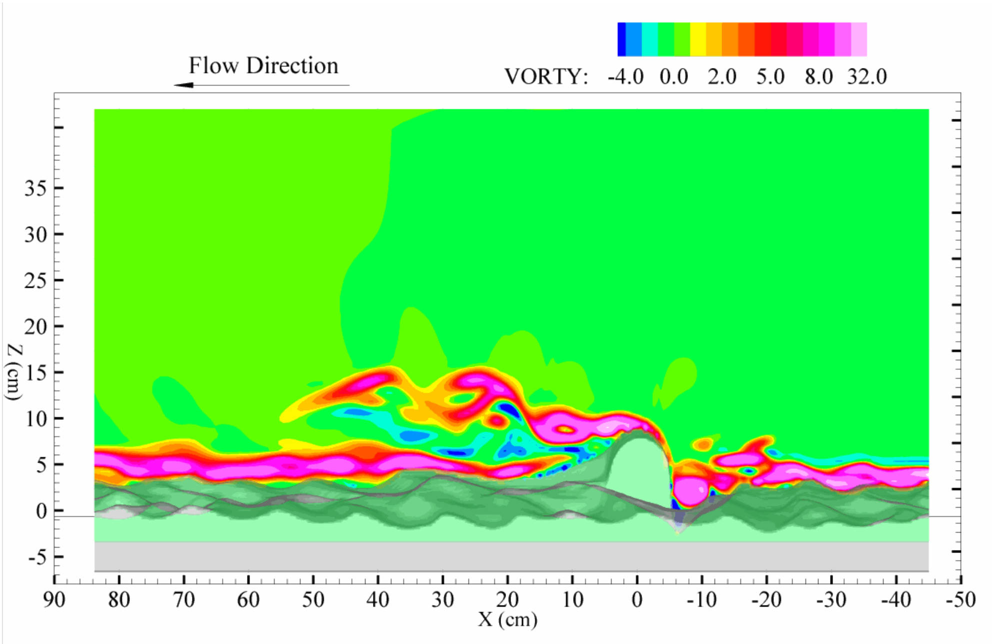


Figure 3: Mean nondimensional turbulent kinetic energy (TKE) for the case of cylindrical object based on (a) laboratory measurements and (b) numerical simulation using the κ-ε turbulence closure

(a)



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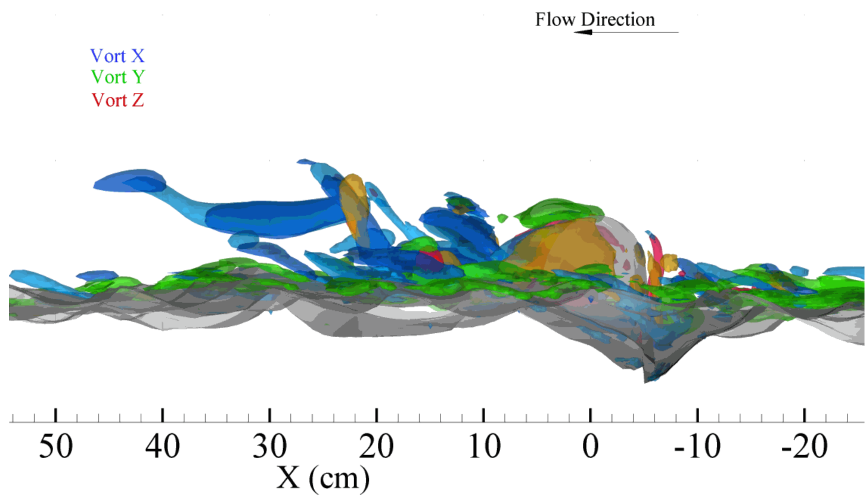

Figure 4: Illustration of vorticity fields around the partially buried cylinder as from LES numerical simulations. Subplot (a) depicts y-vorticity contours shedding away from the cylinder in the XZ-plane along y = 0 cm. Subplot (b) shows 3D coherent vortex cores.