

INTERIM REPORT

Coupled Ensemble Seafloor Environment and 6-DOF
(CESE6D) Model for Assessing Characteristics of
Munitions Underwater and Their Environment

SERDP Project MR19-C1-1073

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List of Acronyms

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
BSS	Brier Skill Score
CAD	Computer Aided Design
CESE6D	Coupled Ensemble Seafloor Environment and 6-DoF
DDB	Delft Dash Board
DoF	Degree of Freedom
ECMWF	- European Centre for Medium-Range Weather Forecasts
ERA5	ECWMF Reanalysis within 5 Days of Real Time
JONSWAP	- Joint North Sea Wave Project
MOR	Morphology
MWL	Mean Water Level
NDBC	National Data Buoy Center
NOAA	- National Oceanic and Atmospheric Administration
NGDC	- National Geophysical Data Center
PC	- Pulse Coherent
TREX	- Target and Reverberation Experiment
MR	- Munitions Response
TM	- Technical Manual
UnMES	- Underwater Munitions Expert System
UXO	- Unexploded ordnance

Keywords

6-DoF Model, Bottom Wave Orbital Velocity, Brier Skill Score, Delft3D, Drag Force and Torque, Lift Force and Torque, Munitions' Mobility and Burial, Munitions' Shields Parameter, Peak Wave Period, Riccati Equation, Scour Burial, Seabed Environmental Model, Sediment Shields Parameter, Sediment supporting Point, Significant Wave Hight, **TREX13** Data, Threshold for Munitions' Initial Mobility

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1. Objective

Our objective is to develop an effective coupled ensemble seafloor environment and 6-DOF (CESE6D) model for the Munition Response (MR) community to assess the environment and to predict munitions' mobility. Since munitions' burial and mobility vary under various environment characteristics such as sediment types, sea floor morphology, and hydrodynamic conditions, timely prediction of seafloor environment and munitions' mobility including its location and burial is crucial to assess characteristics of munitions underwater and their environment. We performed the first of a proposed set of (1) analyzing SERDP MR data (TREX13) to characterize the environment in which munitions' burial and mobility were recorded from the SERDP MR-2320 (Calantoni et al., 2014), (2) developing a 6-DoF model to predict munitions' burial and mobility, and (3) implementing the Delft3D for the northern coastal region of the Gulf of Mexico near Panama City during the TREX13 period.

Our project was formulated in direct response to the Statement of Need for the Munitions Response Program Area (MRSON-13-02), which called for topics that include (1) assessing and predicting the location of munitions relative to the seafloor, and (2) assessing the environment in which munitions are found. Furthermore, information obtained on munitions locations may be used to assess the utility of various underwater sensor and survey approaches. To this end, our year 1 modeling effort had an ancillary objective to provide a 6-DoF model to predict munitions' burial and mobility. The model was verified using the long-term monitoring of waves and currents including high resolution measurements of boundary layer processes in cooperation with SERDP funded efforts during the Target and Reverberation Experiment (TREX13) held off the coast of Panama City, FL in April-May 2013.

Our research seeks to answer questions such as:

- (1) Does a munition that is stranded on the beach face (from dune erosion, excavated in place or delivered via transport from seaward), scour in partially, bury, or become transported offshore?*
- (2) Does a munition that nears the shoreline reach the beach face or remain offshore?*
- (3) How are the answers to 1-2 governed by forcing conditions and munition characteristics?*
- (4) Do surrogate and inert munitions behave similarly under the same forcing conditions?*
- (5) Can a simple force balance be used to determine munitions mobility on beaches?*
- (6) What is the overall importance of the surge force in landward transport of munitions when on the beach face?*

We are collaborating with SERDP funded efforts including FY19 new start projects MR19-1317 “Towards Developing Demonstrations for Munitions Mobility and Burial in the Underwater Environment” to get sufficient and reliable data in both seabed environment and munitions' mobility/burial through participating the field experiment and MR19-1126 “Advanced Capabilities in the Underwater Munitions Expert System” to incorporate our effort into the Underwater Munitions Expert System (UnMES).

2. Technical Approach

Many factors affect the burial and mobility of a munition in underwater sedimentary environment. They are (a) physical and mechanical properties of the sediment, (b) fluid forces that act on the munition and the sediment in vicinity of the munition, (c) interaction between the munition and seabed (near field), and (d) far field bed dynamics of the coastal area of interest. Underwater environment is complex due to great nonlinear interacting processes and difficulty in reliable measurements. Prediction of burial and mobility is similar between underwater munitions and sea mines. The knowledge of sea mine's physical characteristics and understanding of its behavior under variety of sedimentary environments is most important, but still an inexact science (Taber 1999). Observations show that burial is sensitive to the type of bottom sediment and nature of the fluid forcing, and the size and shape of the object. Mines planted in the areas of muddy sediments may sink upon impact.

During the ONR accelerated research initiative (ARI) "Mine Burial Prediction" during 2001-2005 (Bennett, 2000), a 6-DOF model, named IMPACT35, was developed to predict three-dimensional trajectory of sea-mine through air, water, and sediment (Chu et al., 2005, 2005; Chu and Fan 2006; Chu 2009). This model contains full physics including nonlinear dynamics, fluid-structure interaction, instability theory (Chu and Fan 2005), and bearing factor method to calculate the sediment force and torque with cavities for mine movements in sediment (Chu and Fan 2007).

Munitions on seabed are less movable than sea mine in water column. Under the sponsorship of SERDP, experimental studies (Calantoni et al., 2014; Friedrichs et al. 2016), and statistical modeling (Rennie, 2017) focus on the determination of the conditions that determine the onset of a specific and important motion, i.e., roll of munition around its main axis, both on a hard surface and on a sand bed in the presence of concurrent scour burial.

The rest of Technical Approach will be broken into three subsections. The first subsection will describe the data analysis on the seabed environment and surrogate munitions during TREX13. The second subsection will detail all of the 6-DoF model development and preliminary verification using TREX13 data. The third subsection will describe the implement of the Deft3D for the TREX13 area for environmental prediction

2.1. TREX13 Data

Two types of data were analyzed for the 6-DoF and seabed modeling: (1) physical characteristics, mobility, and burial of munition surrogates and replicas, and (2) seabed environments such as currents, waves, and sediments. The data were obtained from a field experiment conducted in northern Gulf of Mexico near Panama City Florida sponsored by SERDP. Most information in this section can be found in Chu et al. (2020) and Calantoni et al. (2014).

Observations were collected from 21 April 2013 to 23 May 2013 to monitor the waves and currents while simultaneously tracking the location of surrogate munitions on the seafloor (Calantoni et al. 2014). The combined observations of munitions mobility and the driving hydrodynamic conditions will be used to validate predictions from the 6-DoF model to predict mobility and burial of seafloor cylindrical objects. During the field experiment, a range of surrogate munitions were deployed that include variations in caliber, bulk density, shape, and rolling moment.

2.1.1. *Munition Data*

Four types of surrogate and replica munitions (Figure 1) that roughly represented the 155 mm HE M107, 81 mm mortar, 25 mm cartridge, and 20 mm cartridge were designed and fabricated using crude drawings and specifications provided by existing Army Technical Manuals (e.g., TM 43-0001-27 and TM 43-0001-28). Additional replica munitions for each of the four types listed above were purchased commercially (e.g., <http://www.inertproducts.com/>). The purchased replicas were used to provide overall dimensions and shape details for the four types of munitions. These purchased replicas were constructed from solid casts of urethane for the 155 mm and 81 mm calibers and solid aluminum for the 25 mm and 20 mm calibers (note the purchased 155 mm caliber was positively buoyant and not deployed).

A total of 4 surrogate munitions and 9 replicas were deployed at each of two water depths adjacent to the quadpod instrument frames (described below). Munition replicas have the general dimensions and shapes of their real counterparts with a single solid material to cover a range of bulk densities. Surrogate munitions are similar in size and shape to replicas except they were fabricated to have bulk densities and rolling moments that more closely match their real counterparts. The complete list of deployed and recovered objects along with brief descriptions and their material properties is given in Table 1. The mass for each object was determined post fabrication prior to deployment. The density listed for the replicas fabricated from a single solid material is the known material density. The volume and rolling moments for all objects were estimated using computer aided design (CAD) software. For the surrogates and replicas that are composites of more than one material the bulk density was estimated by combining the measured mass and the volume estimate from the CAD software.

Photos for the four types of surrogate munitions are shown in Fig. 1. The first type was designed to represent the projectile, 155 mm, HE, M107, typically fired from 155 mm howitzers (left panels). The second type was designed to represent the 81 mm mortar (middle panels). The third and fourth types were designed to represent the cartridges, 25 mm and 20 mm (right panels). Each of the photos contains the fabricated surrogate, the purchased replica, and the replica fabricated from a single solid piece of aluminum (for 155 mm, bottom left), with a solid stainless steel body and aluminum tail section (for 81 mm, bottom middle), with a steel projectile fabricated with nearly identical density and dimensions to those found in the Army Technical Manual (for 25 mm and 20 mm cartridges, bottom right). The difference in rolling moment calculated for the 81 mm surrogate with and without fins is only 4.4%. While the fins seemingly add little to the total rolling moment, their interaction with the seafloor and bottom currents should not be underestimated. For 25 mm and 20 mm cartridges, a solid piece of Delrin plastic cut in the shape of the shell casing very closely matches the weight of the remaining portion of the munitions. Note that while a steel projectile is very common for the 20 mm type, we realize that the projectiles for the 25 mm type may be much more sophisticated and varied. Here we assumed the simplest solid steel projectile for the 25 mm type.

A combination of different acoustic Doppler current profilers (ADCPs) and acoustic Doppler velocimeters (ADVs), and pulse-coherent, acoustic Doppler profilers (PC-ADPs) were used to observe time series of the vertical profile of velocity at high spatial resolution near the bed and lower spatial resolution in the upper water column. Wave heights were obtained using both an acoustic surface tracking (Nortek AWAC) and pressure time series. Temperature, salinity, and pressure were also recorded near the bed. Finally, a sector scanning sonar was mounted on one of the legs of each of the quadpods, scanning a 110° swath every 12 minutes. The surrogate and replica munitions (described above) were deployed within the view field of the sector scanning sonar.

Instruments to observe the local hydrodynamics and resulting munitions mobility were mounted on a pair of large rugged frames (herein referred to as “quadpods”) that were deployed at two different water depths (herein referred to as “deep” and “shallow”) during the Target and Reverberation Experiment (TREX13). The quadpods deployed in the northern Gulf of Mexico offshore of Panama City Beach, Florida USA (Figure 2). The deep quadpod was deployed at 30° 03.02330 N, 85° 41.33630 W in about 20 m water depth, while the shallow quadpod was deployed at 30° 04.80994 N, 85° 40.41064 W in about 7.5 m water depth.

Table 1. List of surrogate and replica munitions used during TREX13. A total of 26 objects were deployed and 18 objects were recovered (from Calantoni et al. 2014). Type surrogate munitions were fabricated to have rolling moments within 10% of the estimated rolling moment of the real counterpart.

Type	Labels	Materials	Type	Recovered	Volume (10^{-5} m^3)	Mass (kg)	Rolling Moment (10^{-4} kg m^2)
155 mm, HE, M107	D5, D6	Delrin, 304 Stainless	Surrogate	D5, D6	768.38	34.15	923.59
	D3, D4	Aluminum	Replica	D3, D4	768.38	20.91	500.48
81 mm mortar	C3, C4	Delrin, 316 Stainless, Aluminum tail fins	Surrogate	C3, C4	120.93	3.76	24.73
	C5, C6	304 Stainless, Aluminum tail fins	Replica	C5, C6	120.93	8.70	50.51
	C1, C2	Urethane	Replica		120.93	1.45	8.34
25 mm cartridge	B5, B6	Delrin, 316 Stainless	Surrogate	B5, B6	16.55	0.39	0.46
	B7, B8	304 Stainless	Replica	B7, B8	16.55	1.32	1.98
	B3, B4	Aluminum	Replica	B3, B4	16.55	0.43	0.68
	B1, B2	Delrin	Replica		16.55	0.23	0.35
20 mm cartridge	A5, A6	Delrin, 316 Stainless	Surrogate	A6	7.70	0.20	0.13
	A7, A8	304 Stainless	Replica	A7	7.70	0.63	0.53
	A3, A4	Aluminum	Replica	A3, A4	7.70	0.19	0.18
	A1, A2	Delrin	Replica		7.70	0.11	0.09



Figure 1. Four types of fabricated surrogate, purchased replica, and fabricated replica of (left) 155 mm HE M107, (middle) 81 mm mortar, and (right) 25mm and 20 mm cartridges (from Calantoni et al. 2014).

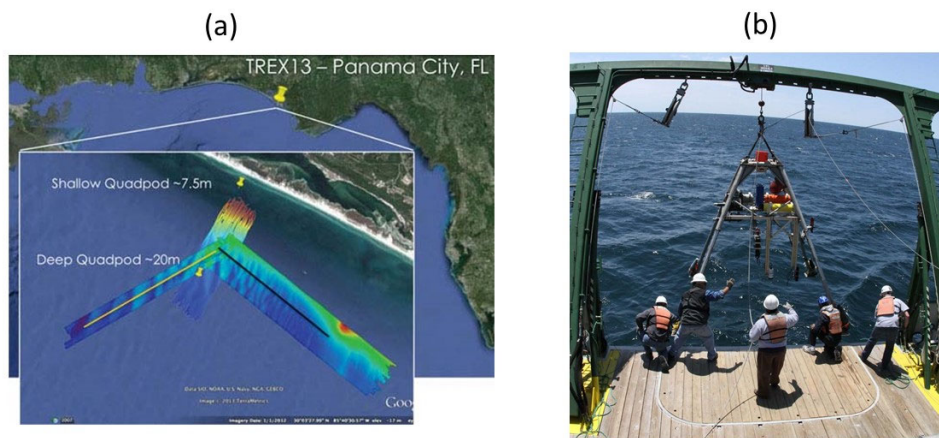


Figure 2. (a) Locations of deep and shallow quadpods, and (b) deployment of the deep quadpod (near 3.3 m tall) into around 20 m water depth from the R/V Smith around 12:40 (local time) on 20 April 2013 (from Calantoni et al. 2014)

Divers laid the surrogate and replica munitions on the seafloor around each quadpods according to a predetermined schematic (Figure 3a). The light blue arc roughly denotes the field of view of the sector scanning sonar. The dark blue circle in the upper left denotes the location of the surrogates. The other replicas were grouped according to relative bulk density. In this case the red boxes denote the objects that were not recovered from the shallow quadpod site. Observations during a maintenance dive (8 May 2013) immediately after the storm event (5-6 May 2013) suggest that the surrogates and replicas may have been buried in place as opposed to being transported away by the waves and currents (Figure 3b). Munitions mobility and burial for the largest surrogates and replicas deployed was observed at the shallow quadpod location in during the passage of an atmospheric front (storm event), 5 – 6 May 2013. However, at the deep quadpod location in ~20 m water depth during the same storm relative observed changes in the state of the surrogate and replica munitions was minimal.

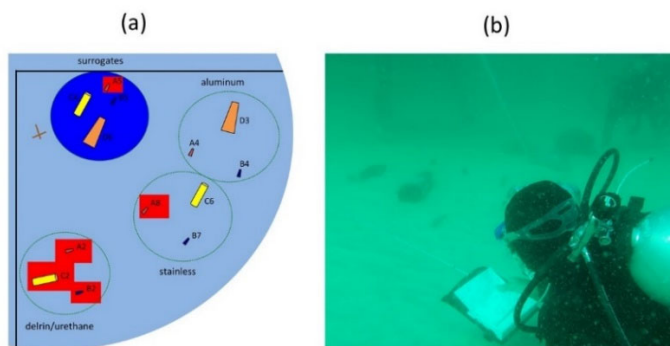


Figure 3. (a) Layout of objects laid by divers under the shallow quadpod (similar for deep quadpod), and (b) the photo of divers laying the object field during the shallow quadpod deployment (from Calantoni et al. 2014).

The 155 mm replica fabricated from solid aluminum was partially buried in the crest of a sand ripple (Fig 8). The sharp crest of the ripple (or bedform) is visible in the foreground of the image, indicated by the black arrow. The replica shown here was the only object not completely buried during the storm event at the shallow quadpod location (Figure 4). Excavating by hand, divers were able to recover a total of 8 munitions buried just below the surface very near the known initial locations at the shallow quadpod during the maintenance dive performed on 8 May 2013.

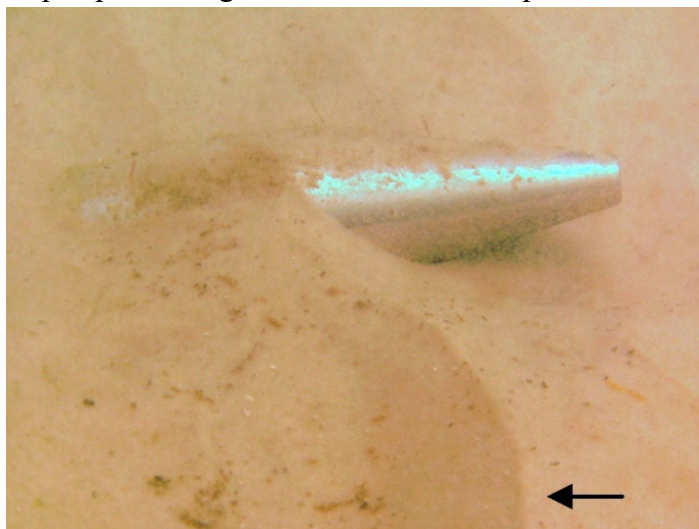


Figure 4. The object field of the shallow quadpod taken on the morning of 8 May 2013 (from Calantoni et al. 2014).

2.1.2. Seabed Environmental Data

Sediment samples were collected at both shallow and deep quadpod locations during the deployment and retrieval. Two cores collected at shallow quadpod location contain nearly 100% sand (Table 2). Grain size distributions were obtained with standard sieve techniques and results for porosity, bulk density (near $2.00 \times 10^3 \text{ kg m}^{-3}$), and void ratio were obtained by measuring the weight loss or water weight. The Phi-values suggest a mean grain size during the deployment of about 0.23 mm in the upper 6 cm of the bed at the shallow quadpod location. Similar grain sizes were found at the deeper quadpod location. Using the values found in Table 2 we estimated the medium of the grain diameter and density in the upper 6 cm of the bed to be,

$$d_{50} = 0.23 \times 10^{-3} \text{ m}, \quad \rho_s = 2.69 \times 10^3 \text{ kg m}^{-3}.$$

Table 2. Sediment properties from diver push cores taken during the deployment (D1) and the retrieval (R1) of the instrumentation at the shallow quadpod location (from Calantoni et al. 2014). Note that medium grain size and standard deviation (STD) are in Phi unit.

Depth Range (cm)	% Gravel		% Sand		Medium Grain Size		STD of Grain Size		% Porosity		Bulk Density (g/cc)		Void Ratio (e)	
	D1	R1	D1	R1	D1	R1	D1	R1	D1	R1	D1	R1	D1	R1
Core #														
0 – 2	0.00	0.04	100.00	99.96	2.14	2.06	0.39	0.40	38.35	39.55	2.04	2.02	0.62	0.65
2 – 4	0.00	0.00	100.00	100.00	2.12	2.04	0.40	0.40	39.28	40.14	2.03	2.02	0.65	0.67
4 – 6	0.00	0.02	100.00	99.98	2.13	2.08	0.42	0.46	39.13	38.96	2.03	2.03	0.64	0.64
6 – 8	0.02	0.01	99.98	99.99	2.23	2.21	0.43	0.44	38.84	39.46	2.04	2.03	0.63	0.65
8 – 10	0.13	0.01	99.87	99.99	1.94	2.24	0.62	0.40	37.62	39.26	2.06	2.03	0.60	0.65
10 – 12	–	0.00	–	100.00	–	2.22	–	0.37	38.17	39.95	2.05	2.02	0.62	0.67
12 – 14	–	0.02	–	99.98	–	2.22	–	0.40	38.60	40.40	2.04	2.01	0.63	0.68
14 – 16	–	0.03	–	99.97	–	2.15	–	0.45	37.05	40.29	2.07	2.01	0.59	0.67
16 – 18	–	0.10	–	99.90	–	2.11	–	0.47	38.00	40.90	2.05	2.00	0.61	0.69
18 – 20	–	0.23	–	99.77	–	2.08	–	0.45	–	39.19	–	2.03		0.64

2.2. Dynamics of Seabed Munitions' Mobility and Burial

2.2.1. Components of 6-DoF Model

A 6-DoF model was developed to predict mobility and burial of seafloor cylindrical objects. The model contains four components: (a) physical parameters of objects such as diameter, length, mass, and rolling moment, (b) dynamics of rolling cylinder around its major axis, (c) empirical sediment scour model, and (d) seabed environmental characteristics such as currents, waves (peak period, significant wave height), sediment density, and medium sediment grain size. Most information in this section can be found in Chu et al. (2020).

Mobility of a seabed object is characterized as the onset fluid velocity at which motion is initiated in relationship to its size and weight (Rennie et al. 2017). The non-dimensional object Shields parameter for percentage burial θ_{pb} , composed from the objects' size and density as well as the local current velocity perpendicular to its main axis (U), was found crucial for the initial mobility of cylindrical object with threshold value of 1 (i.e., $\theta_{pb} > 1$). Burial of a bottom sitting object in sandy sediment is often caused by scour, which is a common burial mechanism and controlled by

the fluid velocity in relationship to the surrounding sediment characteristics, such as regional pressure gradients, tidal forcing and the orbital velocity of waves. Other processes beside scour can also bury UXO in non-cohesive sediments.

The nondimensional sediment Shields parameter θ_{sed} is important for the scour burial. However, no physical model is available to predict munitions' mobility. The existing experimental and statistical research provide useful framework for development of a 6-DoF model, which is presented in this report.

2.2.2. Sediment Supporting Point

Consider a cylindrical object with length L and diameter D and with less than 50% buried in grains of sand on seabed with diameter of D and burial depth of B (Traykovski and Austin, 2017). Let water move on a current vector $\mathbf{V}_w$ towards the cylinder with an angle (ϕ) to the direction perpendicular to its main axis. Let $\mathbf{V}_w$ be decomposed into $\mathbf{V}_w = (U, V)$ with U the perpendicular component, and V the paralleling component (Figure 5). For a sufficiently large aspect ratio ($L \gg D$), the roll of the cylinder is typically greater than the pitch and yaw.

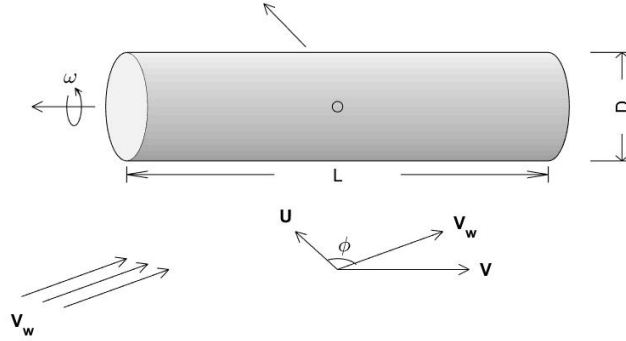


Figure 5. Roll of seabed cylindrical object with large aspect ratio forced by ocean currents. Here, $(\pi/2-\phi)$ is the angle between the currents and the cylinder 's main axis (from Chu et al. 2020)

As the object rolls with ω the angular velocity, it needs a *center of roll* inside the sediment at depth b ($b < B$). Let ψ be the radial angle of the cylinder from the vertical axis with ψ_B at the top of sediment, and ψ_b at the depth b (Figure 6). The horizontal velocity of the object rolling around the point b is given by

$$u_o = \omega\left(\frac{D}{2} - b\right), \quad (1)$$

with the radial component of $u_o \sin \psi$ at any depth inside the sediment. Thus, the compressive normal stress of sediment on the object is represented by

$$\mathbf{F}_S = -\mathbf{n} \kappa u_o \sin \psi, \quad (2)$$

where $\mathbf{n}$ is outgoing normal unit vector of the cylinder, and κ is the compressive coefficient. Let $\mathbf{n}$ be decomposed into

$$\mathbf{n} = -\mathbf{e}_h \sin \psi - \mathbf{e}_v \cos \psi, \quad (3)$$

where $(\mathbf{e}_h, \mathbf{e}_v)$ are horizontal and vertical unit vectors (see Figure 6). The sediment compressive normal stress $\mathbf{F}_S$ is decomposed by

$$\mathbf{F}_S = \mathbf{e}_h \kappa u_o \sin^2 \psi + \mathbf{e}_v \kappa u_o \sin \psi \cos \psi. \quad (4)$$

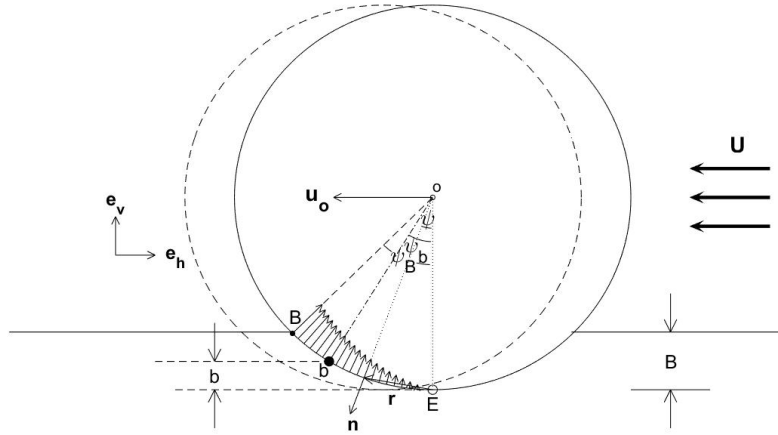


Figure 6. Rolling center of a cylinder in the sediment (b) determined by the assumption of zero-sum torque to the roll (from Chu et al., 2020).

With b as the rolling center, the sediment above (below) the depth b generates torque to resist (enhance) the rolling with the total torque from the sediment,

$$\mathbf{T}_S = \int_0^{\psi_B} [(\mathbf{r} - \mathbf{r}_b) \times \mathbf{F}_S] d\psi = \int_0^{\psi_B} [\mathbf{r} \times \mathbf{F}_S] d\psi - \mathbf{r}_b \times \int_0^{\psi_B} \mathbf{F}_S d\psi \quad (5)$$

where $\mathbf{r}$ is the position vectors at any point on the circle with the bottom point E as the origin; and $\mathbf{r}_b$ is the position vector at point b ,

$$\mathbf{r} = \frac{D}{2} (-\mathbf{e}_h \sin \psi + \mathbf{e}_v (1 - \cos \psi)), \quad \mathbf{r}_b = \frac{D}{2} [-\mathbf{e}_h \sin \psi_b + \mathbf{e}_v (1 - \cos \psi_b)] \quad (6)$$

The depths B and b are represented by

$$B = \frac{D}{2} (1 - \cos \psi_B), \quad b = \frac{D}{2} (1 - \cos \psi_b) \quad (7)$$

If we assume that at the depth b the total torque from the sediment is zero (i.e., zero-sum sediment torque for rolling),

$$\mathbf{T}_s = 0. \quad (8)$$

Substitution of Eqs.(4)-(6) into Eq.(8) gives,

$$\psi_b = \tan^{-1} \left(\frac{\psi_B - \sin \psi_B \cos \psi_B}{\sin^2 \psi_B} \right). \quad (9)$$

The ratio $\lambda = b/B$ can be obtained from Eq.(7) and Eq.(9)

$$\lambda \equiv b/B = \frac{1 - \cos \left[\tan^{-1} \left(\frac{\psi_B - \sin \psi_B \cos \psi_B}{\sin^2 \psi_B} \right) \right]}{1 - \cos \psi_B} \quad (10)$$

The ratio λ varies with the burial percentage $p_B = B/D$ mildly from near 0.4445 for $p_B = 0$ and 0.463 for $p_B = 0.5$ (Figure 7),

$$\lambda(p_B) = 0.4445 + 0.0286p_B + 0.0165p_B^2. \quad (11)$$

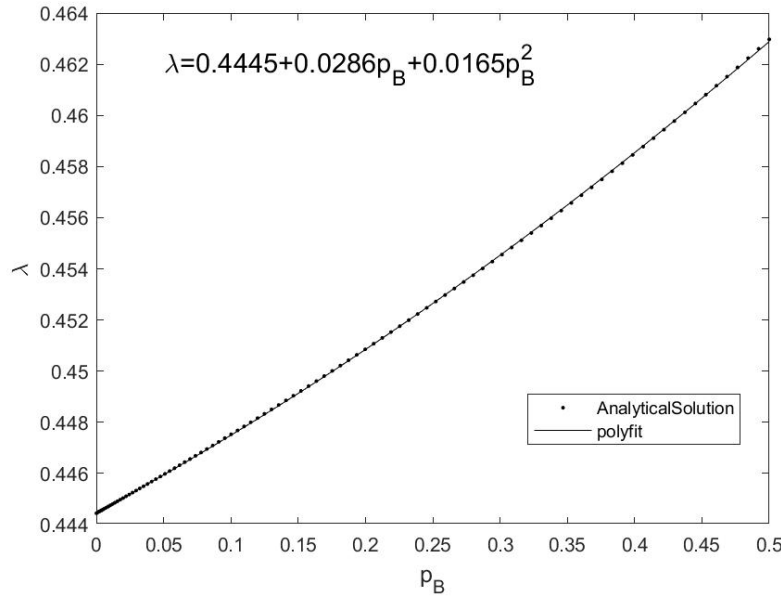


Figure 7. Dependence of λ on p_B (from Chu et al., 2020).

2.2.3. Threshold for Munitions' Initial Mobility

The drag force (F_d), lift force (F_l), and reduced gravity (F_w) exerted on the object for rolling by the perpendicular component U are given by

$$F_d = \frac{\rho_w C_d U^2 (D - B)}{2}, \quad F_l = \frac{\rho_w C_l U^2 D}{2}, \quad F_w = \frac{g(\rho_o - \rho_w) \pi D^2}{4}, \quad (12a)$$

where $g = 9.81 \text{ m/s}^2$, is the gravitational acceleration; $\rho_w = 1.025 \times 10^3 \text{ kg/m}^3$, the density of seawater; ρ_o , the density of the object; C_d the drag coefficient, which depends on Reynolds

number and aspect ratio; and C_l the lift coefficient. Since lift coefficient is less certain, we assume

$$C_l = \gamma C_d \quad (12b)$$

where γ is the ratio of lift coefficient versus drag coefficient with γ taken as 0.2.

The drag force rolls the cylinder forward around the rolling center b with the torque per unit length of $F_d(D/2 + \delta - b)$. Here, $\delta > 0$, is the distance between the volume center of the cylinder above the sediment (i.e., point B in Figure 8) and the volume center of the whole cylinder (i.e., point O in Figure 8). Note that the point C is the center of the resultant drag force on the cylinder; and δ is a function of B . For simplicity, we use $\delta = B/2$. The reduced gravity minus lift force resists the cylinder rolling forward caused by the drag with the torque per unit length of $F_w\sqrt{b(D-b)}$ (reduced gravity) and $F_l\sqrt{b(D-b)}$ (lift). The threshold for the mobility of the object is represented by

$$F_d(D/2 + \delta - b) + F_l\sqrt{b(D-b)} > F_w\sqrt{b(D-b)} \quad (13)$$

which reduces to the mobility condition proposed by Traykovski and Austin (2017) if $F_l = 0$, and $\delta = 0$.

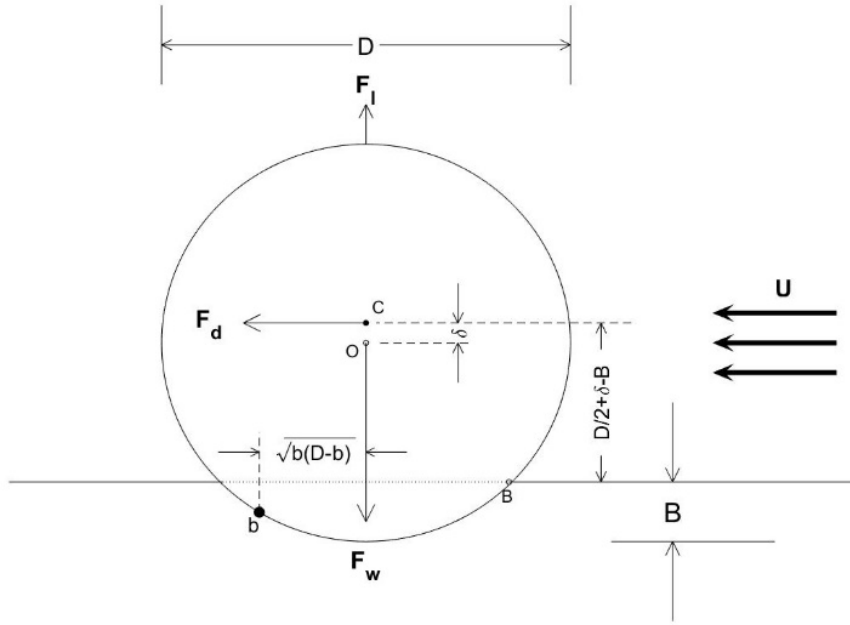


Figure 8. Forces and torques on a partially buried cylinder by ocean currents (from Chu et al., 2020).

The drag and lift forces roll the object forward with the total torque (T_F),

$$\begin{aligned}
 T_F &= F_d (D/2 + \delta - b) + F_l \sqrt{b(D-b)} \\
 &= \frac{1}{2} C_d \rho_w U^2 \left[(D-b/\lambda)(D/2 + \delta - b) + \frac{C_l}{C_d} D \sqrt{b(D-b)} \right] \left(1 - \frac{u_o}{U} \right)^2
 \end{aligned} \tag{14a}$$

where Eq.(10) is used to represent B by b ($B = b/\lambda$). The reduced gravity rolls the object backward with the torque (T_B),

$$T_B = F_w \sqrt{b(D-b)} = \frac{\pi}{4} g D^2 (\rho_o - \rho_w) \sqrt{b(D-b)} \tag{14b}$$

If $T_F > T_B$, the object accelerates if it is in motion or starts to move if it is at rest. If $T_F < T_B$, the object decelerates if it is in motion or keeps motionless if it is at rest. If $T_F = T_B$, the object keeps velocity constant if it is in motion or keeps motionless if it is at rest. Thus, it is reasonable to assume that decrease of T_F and increase of T_B by a small fraction ε makes the object motionless, i.e., the threshold becomes

$$T_F(1 - \varepsilon) = T_B(1 + \varepsilon), \quad 0 < \varepsilon < 1. \tag{15}$$

The acceleration-deceleration ratio is defined by

$$\Gamma \equiv \frac{T_F}{T_B} = \theta_{opb} \left(1 - \frac{u_o}{U} \right)^2, \tag{16}$$

with

$$\begin{aligned}
 \theta_{opb} &= \frac{C_d \theta_0}{\pi} \left[\frac{1 - p_b/\lambda}{\sqrt{p_b(1 - p_b)}} (1 + 2p_\delta - 2p_b) + 2\gamma \right], \\
 \theta_0 &\equiv \left[\frac{U^2}{gD(S_o - 1)} \right], \\
 p_\delta &= \frac{\delta}{D}, \quad p_b = \frac{b}{D}, \quad S_o = \frac{\rho_o}{\rho_w}, \quad \gamma = \frac{C_l}{C_d}
 \end{aligned} \tag{17}$$

Here, θ_{opb} is the object Shields parameter based on p_b ; θ_0 is the object mobility number (Rennie et al., 2017); S_o is the object's relative density; and u_o is the object horizontal velocity. Substitution of Eq.(16) into Eq.(15) leads to the condition for the object to move no matter if it is in motion or motionless,

$$\Gamma > \Gamma_{th}, \quad \Gamma_{th} \equiv (1 + \varepsilon)^2 \tag{18}$$

where $(1 - \varepsilon)^{-1} \approx (1 + \varepsilon)$ is used. With Eq.(16) the condition (18) is changed into

$$\theta_{opb} \left(1 - \frac{u_o}{U} \right)^2 > (1 + \varepsilon)^2 \tag{19}$$

For initially motionless object ($u_o = 0$) without ε , the expression (19) is reduced to $\theta_{oph} > 1$ (Traykovski and Austin, 2017). Here, ε is taken as 0.01. The key parameters in this expression are the diameter of the object and the initial depth of burial as these determine the torque arms, and the steady current velocity (U) combined with the relative density of the object (S_o) as these determine the forces. The threshold is similar to that was described in Traykovski and Austin

(2017), if $p_\delta = 0$, i.e., the center ‘O’ is the center of the drag force which implies it drags the whole cylinder including the area buried in the sediment), $\gamma = 0$ (no lift force), and replacement of p_b by $p_B (= B/D)$, where B is the object burial depth.

2.2.4. Core Dynamics

The cylindrical object (large aspect ratio) is in motion when its Shields parameter θ_{opb} satisfies the condition (19). The corresponding moment of momentum equation is given by

$$\begin{cases} I_A \frac{d\omega}{dt} = T_F - T_B, & \text{if } T_F / T_B > (1 + \varepsilon)^2 \\ \omega = 0, & \text{otherwise} \end{cases} \quad (20a)$$

where $I_A = I_o + MD^2 / 4$; $I_o = MD^2 / 8$, is the rolling moment of the axially symmetric uniform cylinder; $M = \rho_o \pi D^2 / 4$, is the cylinder ‘s’ mass per unit length. Substitution of Eq.(1), Eq.(14a), Eq.(14b), and Eq.(19) into Eq.(20a) leads to

$$\begin{cases} \frac{d(U - u_o)}{dt} = -\frac{(T_F - T_B)(D/2 - b)}{I_A} + \frac{dU}{dt}, & \text{if } \theta_{opb} \left(1 - \frac{u_o}{U}\right)^2 > (1 + \varepsilon)^2 \\ u_o = 0, & \text{otherwise} \end{cases} \quad (20b)$$

Substitution of Eq.(14a) and Eq.(14b) into Eq.(20b) leads to a special Riccati equation

$$\begin{cases} \frac{d(U - u_o)}{dt} + \alpha(U - u_o)^2 = \beta, & \text{if } \theta_{opb} \left(1 - \frac{u_o}{U}\right)^2 > (1 + \varepsilon)^2 \\ u_o = 0, & \text{otherwise} \end{cases} \quad (21a)$$

where

$$\begin{aligned} \alpha &= \frac{(D/2 - b)}{2I_A} \rho_w C_d \left[(D - b/\lambda)(D/2 + \delta - b) + \gamma D \sqrt{b(D - b)} \right] > 0 \\ \beta &= \frac{(D/2 - b)}{4I_A} g \rho_w (S_o - 1) \pi D^2 \sqrt{b(D - b)} + \frac{dU}{dt} \end{aligned} \quad (21b)$$

The inequality $\alpha > 0$ is due to $D/2 \gg b$. Note that (α, β) have the units of (m^{-1} , m s^{-2}). Eq.(21) has analytical solution if α and β are time-independent (Kamke, 1977)

$$u_o(t) = U(t) - \begin{cases} \frac{U(t_0) - u_o(t_0)}{1 + \alpha [U(t_0) - u_o(t_0)](t - t_0)} & \alpha > 0 \\ \frac{[U(t_0) - u_o(t_0)]\sqrt{\alpha\beta} + \beta \tanh\left[\left(\sqrt{\alpha\beta}\right)(t - t_0)\right]}{\sqrt{\alpha\beta} + \alpha [U(t_0) - u_o(t_0)] \tanh\left[\left(\sqrt{\alpha\beta}\right)(t - t_0)\right]} & \beta = 0 \\ \frac{[U(t_0) - u_o(t_0)]\sqrt{-\alpha\beta} + \beta \tanh\left[\left(\sqrt{-\alpha\beta}\right)(t - t_0)\right]}{\sqrt{-\alpha\beta} + \alpha [U(t_0) - u_o(t_0)] \tanh\left[\left(\sqrt{-\alpha\beta}\right)(t - t_0)\right]} & \beta > 0 \\ \frac{[U(t_0) - u_o(t_0)]\sqrt{-\alpha\beta} + \beta \tan\left[\left(\sqrt{-\alpha\beta}\right)(t - t_0)\right]}{\sqrt{-\alpha\beta} + \alpha [U(t_0) - u_o(t_0)] \tan\left[\left(\sqrt{-\alpha\beta}\right)(t - t_0)\right]} & \beta < 0 \end{cases} \quad (22)$$

As time evolves from t_0 , the condition (19) should be used to identify if the object continues to **roll**. Substitution of (22) into the mobility condition (19) leads to

$$\begin{aligned} \frac{U(t_0) - u_o(t_0)}{\{1 + \alpha [U(t_0) - u_o(t_0)]\}(t - t_0)} &\geq \frac{(1 + \varepsilon)U(t_0)}{\sqrt{\theta_{opb}}} && \text{for } \beta = 0 \\ \frac{[U(t_0) - u_o(t_0)]\sqrt{\alpha\beta} + \beta \tanh\left[\left(\sqrt{\alpha\beta}\right)(t - t_0)\right]}{\sqrt{\alpha\beta} + \alpha [U(t_0) - u_o(t_0)] \tanh\left[\left(\sqrt{\alpha\beta}\right)(t - t_0)\right]} &\geq \frac{(1 + \varepsilon)U(t_0)}{\sqrt{\theta_{opb}}} && \text{for } \beta > 0 \\ \frac{[U(t_0) - u_o(t_0)]\sqrt{-\alpha\beta} + \beta \tanh\left[\left(\sqrt{-\alpha\beta}\right)(t - t_0)\right]}{\sqrt{-\alpha\beta} + \alpha [U(t_0) - u_o(t_0)] \tanh\left[\left(\sqrt{-\alpha\beta}\right)(t - t_0)\right]} &\geq \frac{(1 + \varepsilon)U(t_0)}{\sqrt{\theta_{opb}}} && \text{for } \beta < 0 \end{aligned}$$

which can be reorganized by

$$\begin{aligned} (t - t_0) &\leq \frac{\sqrt{\theta_{opb}}}{(1 + \varepsilon)U(t_0)} \frac{U(t_0) - u_o(t_0)}{\{1 + \alpha [U(t_0) - u_o(t_0)]\}} && \text{for } \beta = 0 \\ t - t_0 &\leq \frac{1}{\sqrt{\alpha\beta}} \tanh^{-1} \left(\frac{\left\{ \sqrt{\theta_{opb}} [U(t_0) - u_o(t_0)] - (1 + \varepsilon)U(t_0) \right\} \sqrt{\alpha\beta}}{\alpha [U(t_0) - u_o(t_0)](1 + \varepsilon)U(t_0) - \beta \sqrt{\theta_{opb}}} \right) && \text{for } \beta > 0 \quad (23a) \\ t - t_0 &\leq \frac{1}{\sqrt{-\alpha\beta}} \tanh^{-1} \left(\frac{\left\{ \sqrt{\theta_{opb}} [U(t_0) - u_o(t_0)] - (1 + \varepsilon)U(t_0) \right\} \sqrt{\alpha\beta}}{\alpha [U(t_0) - u_o(t_0)](1 + \varepsilon)U(t_0) - \beta \sqrt{\theta_{opb}}} \right) && \text{for } \beta < 0 \end{aligned}$$

Thus, the **object mobility time** (t^{mob}) is determined as

$$\begin{aligned}
 t^{mob} &= \max(t - t_0) \\
 &= \begin{cases} \frac{\sqrt{\theta_{opb}}}{(1+\varepsilon)U(t_0)} \frac{U(t_0) - u_o(t_0)}{\{1 + \alpha[U(t_0) - u_o(t_0)]\}} & \text{for } \beta = 0 \\ \frac{1}{\sqrt{\alpha\beta}} \tanh^{-1} \left(\frac{\{\sqrt{\theta_{opb}}[U(t_0) - u_o(t_0)] - (1+\varepsilon)U(t_0)\}\sqrt{\alpha\beta}}{\alpha[U(t_0) - u_o(t_0)](1+\varepsilon)U(t_0) - \beta\sqrt{\theta_{opb}}} \right) & \text{for } \beta > 0 \\ \frac{1}{\sqrt{-\alpha\beta}} \tan^{-1} \left(\frac{\{\sqrt{\theta_{opb}}[U(t_0) - u_o(t_0)] - (1+\varepsilon)U(t_0)\}\sqrt{\alpha\beta}}{\alpha[U(t_0) - u_o(t_0)](1+\varepsilon)U(t_0) - \beta\sqrt{\theta_{opb}}} \right) & \text{for } \beta < 0 \end{cases} \quad (23b)
 \end{aligned}$$

Variation of the current velocity vector changes the rolling direction of object. Consider the cross section of the cylindrical object. Let $\mathbf{i}_a$ be the unit vector of the object's main axis, and $\mathbf{i}_r$ be the unit vector from turning $\mathbf{i}_a$ 90° anticlockwise. The water velocity component $U(t)$ is the current velocity vector projected to the vector $\mathbf{i}_r$, $U = \mathbf{V}_w \bullet \mathbf{i}_r$, which can be either positive and negative.

Let l be the displacement of object,

$$dl / dt = \text{sgn}(U)u_o,$$

integration of this equation with respect to time t leads to

$$l(t) = l(t_0) + \text{sgn}[U(t_0)] \int_{t_0}^t u_o(\tau) d\tau \approx l(t_0) + \frac{\text{sgn}[U(t_0)]}{2} (u_o(t_0) + u_o(t))(t - t_0) \quad (24)$$

where

$$\text{sgn}(\tau) = \begin{cases} -1 & \text{if } \tau < 0 \\ 0 & \text{if } \tau = 0 \\ 1 & \text{if } \tau > 0 \end{cases}$$

is the sign function. The analytical solution (22) depends on (α, β) and in turn on three types of parameters: (a) physical parameters of the object (S_o, D) , (b) water velocity $U(t)$ and related center of drag force δ , and (c) sediment center of rolling depth b [see (21b)]. Among them, only the physical parameters of object are time invariant. The water velocity $U(t)$ can be from ocean observational or numerically modeled data. Sediment center of rolling depth $b(t)$ is determined by a scour burial model.

Note that the coefficients (α, β) in the Ricatti equation (21a) usually vary with time, $\alpha = \alpha(t)$, $\beta = \beta(t)$. Let the prediction time period be T and the initial time instance be t_0 . The time period T is divided into K equal intervals with $\Delta t = T/K$: $t_k = k\Delta t$, $k = 0, 1, \dots, K$. Let the object mobility time at time instance t_k be t_k^{mob} . We integrate the Ricatti equation (21a) from t_k with two occurrences: (a) long object mobility time ($t_k^{mob} \geq \Delta t$), and (b) short object mobility time ($t_k^{mob} < \Delta t$). The Ricatti equation (22) is integrated piece-wisely from u_0 at t_k to u_0 at t_{k+1} with the coefficients taken the values at t_k [i.e., $\alpha_k = \alpha(t_k)$, $\beta_k = \beta(t_k)$],

$$u_o(t_{k+1}) = \begin{cases} 0 & t_k^{mob} < \Delta t \\ u_o(t_k + \Delta t) & t_k^{mob} \geq \Delta t \end{cases} \quad (25a)$$

with

$$u_o(t_k + \Delta t) = U(t_k) + \frac{dU(t_k)}{dt} \Delta t$$

$$- \begin{cases} \frac{U(t_k) - u_o(t_k)}{1 + \alpha_k [U(t_k) - u_o(t_k)](t - t_k)} & \beta_k = 0 \\ \frac{[U(t_k) - u_o(t_k)] \sqrt{\alpha_k \beta_k} + \beta_k \tanh \left[\left(\sqrt{\alpha_k \beta_k} \right) \Delta t \right]}{\sqrt{\alpha_k \beta_k} + \alpha_k [U(t_k) - u_o(t_k)] \tanh \left[\left(\sqrt{\alpha_k \beta_k} \right) \Delta t \right]} & \beta_k > 0 \\ \frac{[U(t_k) - u_o(t_k)] \sqrt{-\alpha_k \beta_k} + \beta_k \tan \left[\left(\sqrt{-\alpha_k \beta_k} \right) \Delta t \right]}{\sqrt{-\alpha_k \beta_k} + \alpha_k [U(t_k) - u_o(t_k)] \tan \left[\left(\sqrt{-\alpha_k \beta_k} \right) \Delta t \right]} & \beta_k < 0 \end{cases} \quad (25b)$$

Numerical integration of (24) gives

$$l(t_{k+1}) = \sum_1^k \Delta l_k, \quad \Delta l_k = \frac{\text{sign}[U(t_k)]}{2} [u_o(t_k) + u_o(t_{k+1})] \quad (25c)$$

where the composite trapezoid rule is used.

2.2.5. Scour Burial

Existing studies on scour burial were all concentrated on the motionless objects. The ratio between the fluid force (bottom shear stress) and the weight of the sediment particles, i.e., the sediment Shields parameter (θ_{sed}),

$$\theta_{sed} = \frac{F_w U_{br}^2}{g(S_{sed} - 1)d_{50}}, \quad S_{sed} = \frac{\rho_s}{\rho_w}, \quad F_w = \exp \left[5.5 \left(\frac{6U_{br}T_p}{\pi d_{50}} \right)^{-0.2} - 6.3 \right], \quad (26)$$

is crucial for scour burial of motionless object and in turn for prediction of the percentage burial parameter $p_B(t) = B/D$ (Rennie, 2017; Rennie et al., 2017; Friedrichs et al, 2016). Here, F_w is the wave friction factor (Nielsen, 1992), ρ_s the sediment grain density, and d_{50} the medium sand grain size.

The bottom wave orbital velocity U_{br} represents interactions between surface waves and the seabed. For small-amplitude, monochromatic waves, linear wave theory predicts that the horizontal component of orbital velocity reaches a maximum velocity since the vertical component approaches zero at the ocean bottom, which leads to

$$U_{br} = \frac{2\pi}{T \sinh(kh)} A \quad (27)$$

where T is the wave period; k is the wave number; and A is the wave amplitude. However, wind-generated waves are not monochromatic. Instead, a spectrum of wave frequencies and heights are present. A spectrum of wave-induced orbital velocity at the bottom boundary can be calculated from a surface gravity wave spectrum S_η by applying (27) to each frequency band i of the wave spectrum (e.g., Soulsby 1987),

$$U_{br}^2 = 2 \sum_i \left[\frac{2\pi}{T_i \sinh(k_i h)} \right]^2 S_\eta(f_i) \Delta f_i \quad (28)$$

where $f_i = 1/T_i$, is the wave frequency. Direct measurements of wave spectra from nearby surface-wave buoys are ideal for determining bottom orbital velocity time series for a site of interest. When the measurements of surface gravity wave spectra are not available, a general form of wind-generated wave spectra can be used (Wiberg and Sherwood, 2008)

$$S_\eta(f) = \frac{\xi_1 H_s^2 f_p^4}{16 f^5} \left(\frac{f}{f_p} \right)^{\xi_4} \exp \left[-\xi_2 \left(\frac{f}{f_p} \right)^4 \right] \xi_3 \exp \left[-\frac{(f - f_p)^2}{2 \xi_5^2 f_p^2} \right] \quad (29)$$

where $f_p = 1/T_p$, is the wave peak frequency (T_p is the wave peak period); H_s is the significant wave height; and $(\xi_1, \xi_2, \xi_3, \xi_4, \xi_5)$ are spectral parameters for different spectra such as

$$\xi_1 = 3.28, \quad \xi_2 = 1.25, \quad \xi_3 = 3.3, \quad \xi_4 = 0, \quad \xi_5 = \begin{cases} 0.7 & \text{for } f / f_p \leq 1 \\ 0.9 & \text{for } f / f_p > 1 \end{cases} \quad (30a)$$

for the Joint North Sea Wave Project (JONSWAP) spectrum (Hasselmann et al., 1973),

$$\xi_2 = 1, \quad \xi_3 = 3.3, \quad \xi_4 = \begin{cases} 6.5 + 2.6 \ln(\bar{f}_p) & \text{for } \bar{f}_p \geq 0.16 \\ 1.7 & \text{for } \bar{f}_p < 0.16 \end{cases}, \quad \xi_5 = 0.08 + 0.0013 \bar{f}_p^{-3} \quad (30b)$$

for the Donelan spectrum (Donelan et al., 1985) with ξ_1 being a function of non-dimensional peak frequency, $\bar{f}_p = f_p W_{10} / g$. Here, W_{10} is the wind speed at 10 m height. A MATLAB function was created to calculate bottom orbital velocity using the parametric spectrum (29) with the water depth (h), significant wave height (H_s), and peak period (T_p) as input and the bottom orbital velocity (U_{br}) as output (see Appendix D in Whitehouse, 1998). In this study, we use the JONSWAP spectrum.

As pointed in Rennie et al. (2017), the equilibrium percentage burial $p_{B,eq}$ for motionless cylinders induced by scour tends to increase as θ_{sed} increases. An empirical formula has been established,

$$p_{B,eq} = a_1 \theta_{sed}^{a_2} - a_3 \quad (31)$$

with different choices of the coefficients (a_1, a_2, a_3) determined experimentally for cylinders subject to steady currents: $a_1 = 11, a_2 = 0.5, a_3 = 1.73$ (Whitehouse 1998), $a_1 = 0.7, a_2 = a_3 = 0$ (Sumer et al., 2001), $a_1 = 2, a_2 = 0.8, a_3 = 0$ (Demir and Garcia, 2007), and for cylinders under

waves (depending on wave period): $a_1 = 1.6$, $a_2 = 0.85$, $a_3 = 0$ for T_p longer than 4 s (Cataño-Lopera, 2007). For motionless cylinders before scour burial reaches an equilibrium the percentage burial follows an exponential relationship (Whitehouse, 1998),

$$p_B(t_k) = p_{B,eq} \left[1 - \exp\left(-\frac{t_k}{T^*}\right) \right], \quad (32)$$

where the e-folding time scale T^* is given by

$$T^* = \frac{M \theta_{sed}^N D^2}{\left[g(S_{sed} - 1) d_{50}^3 \right]^{0.5}}, \quad N = 1.5, \quad M = 0.11. \quad (33)$$

The sediment supporting depth b (or p_b) is calculated from burial depth B (or p_B) using (10) and (11), i.e.,

$$b(t_k) = \lambda B(t_k), \quad p_b(t_k) = b(t_k) / D = \lambda p_B(t_k), \quad \lambda = 0.453 \quad (34)$$

The 6-DoF model consists of Eqs.(25), (26), (28)-(34). The Whitehouse scour burial model does not include tidal and along shore currents. Feasibility of its usage for very shallow water conditions with asymmetric forcing induced by breaking waves needs further investigation.

2.3. Delft3D Model

The Delft3D version 4.04.01 was implemented to the northern Gulf of Mexico near Panama City, Florida (i.e., TREX13 field site) with three major modules: Flow (tides and circulations), Wave (wave propagations, Morphology (sediment transport and morphological evolution). This area represents a typically lower energetic environment than other field sites on the east and west coast of the U.S. The Delft Dash Board (DDB) was used to create the grids and the tide forcing boundary conditions for the coupled wave and 2D flow model, including sediment transport and bottom change. Four nested grids compose the wave model, while two nested grids constitute the flow model. Wave boundary conditions were set up including Wavewatch III output and NOAA Buoy 42039 measurements. Moreover, wind data and bathymetric data from ECMWF and NOAA/NGDC, respectively, were incorporated as input data to the coupled model. The parameter settings for the flow, wave, and morphology modules are also provided. Most information in this section can be found in Santos Pessanha (2019).

2.3.1. Currents and Tides

Since the density stratification is weak in the TREX13 region, the two-dimensional barotropic Flow Module was used. Two nested rectangular grids compose the flow domain (Figure 9). The flow outer grid (coarser resolution) is large enough to cover the location of the Panama City Beach tide station, and the flow inner grid (finer resolution) includes the location of shallow and deep quadpods used in the TREX13 experiment. The outer rectangular domain is 47.2 km $\times$ 21km with the resolution of 100 m $\times$ 100 m. The inner rectangular domain is 7.5 km $\times$ 6 km with the resolution of 25 m $\times$ 25

m.

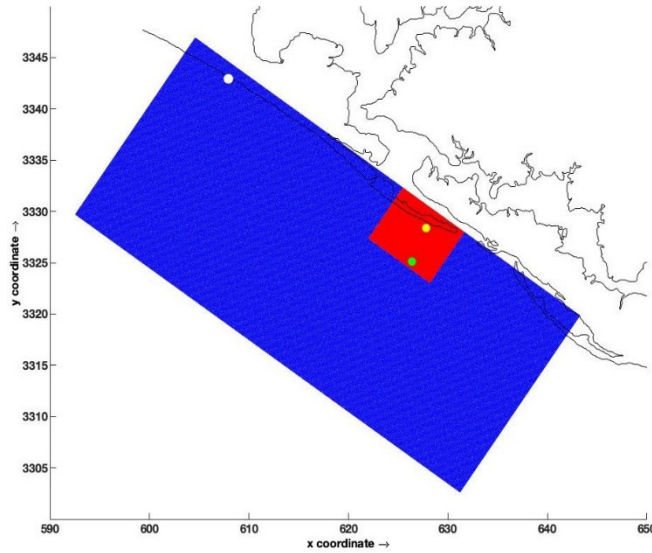


Figure 9. Outer (blue) and inner (red) grids of the Delft3D flow module implemented in the TREX13 area with the white dot indicating the location of the Panama City Beach tide station. The outer rectangular domain is $47.2 \text{ km} \times 21 \text{ km}$ with the resolution of $100 \text{ m} \times 100 \text{ m}$. The inner rectangular domain is $7.5 \text{ km} \times 6 \text{ km}$ with the resolution of $25 \text{ m} \times 25 \text{ m}$ (from Santos Pessanha, 2019).

The bathymetric data (Figure 10) used was the Northern Gulf Coast Digital Elevation Model (NOAA/NGDC, 2010). The resolution of this data set varies between $1/3$ arc-second and 1 arc-second (around 10 and 30 meters). The wind input files were set up with ERA5 Reanalysis data from European Centre for Medium-Range Weather Forecasts (ECMWF), with 0.25° (around 28 km) resolution (ECMWF, 2019).

The Global Inverse Tide Model TPXO 8.0, included in the DDB, was used to create the boundary conditions for Delft3D Flow module. For the longshore boundary, the water level with astronomic forcing was imposed. Conversely, for both cross-shore open boundaries, the Neumann boundary conditions was set to zero. Table 3 shows that the major tidal constituents are the diurnal constituents K1, O1, and P1.

Table 3. Tidal constituents at longshore boundary (from Santos Pessanha, 2019).

Constituents	Amplitude (m)	Phase (deg)	Constituents	Amplitude (m)	Phase (deg)
K1	0.141	23.7	N2	0.009	110.6
O1	0.137	15.2	MF	0.007	351.9
P1	0.047	17.3	K2	0.006	90.0
Q1	0.031	357.6	MM	0.003	341.6
M2	0.029	97.8	M4	0.002	333.4
S2	0.016	90.0	MS4	0.001	315.0

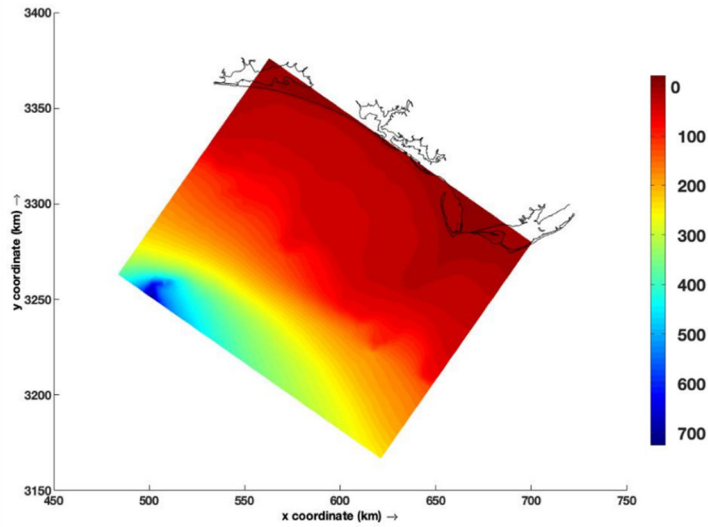


Figure 10. Bathymetry of the TREX13 area obtained from NOAA/NGDC 2010 (from Santos Pessanha, 2019).

2.3.2. Waves

The wave domain covers a broader area than that of the area of interest (Figure 11) to avoid the effects of boundary, and to allow the use of Buoy 42039 data available from the National Data Buoy Center (NDBC). Considering the computational cost, four grid systems with different grid cell sizes were nested as a way to create a region with finer resolution. All four grids are rectangular with squared cells and distinct resolution as described in Table 2. The wave inner grid resolution is 50 meters. The wave outer domain covers a broader area than that of the area of interest (Figure 10). Considering the computational cost, four grids with different grid cell sizes were nested as a way to create a region with finer resolution. All four grids are rectangular with squared cells and distinct resolution as described in Table 4. The wave inner grid resolution is 50 meters.

Table. 4. Grid details for the Delft3D wave module. M and N signify number of cells in longshore and cross-shore directions, respectively (from Santos Pessanha, 2019).

Domain Name	Domain Size (km)	M	N	Cell Size (km)
Wave outer	168×138	56	46	3×3
Wave middle 1	85×48	85	48	1×1
Wave middle 2	51×25	204	100	0.25×0.25
Wave inner	8.5×6.5	170	130	0.05×0.05

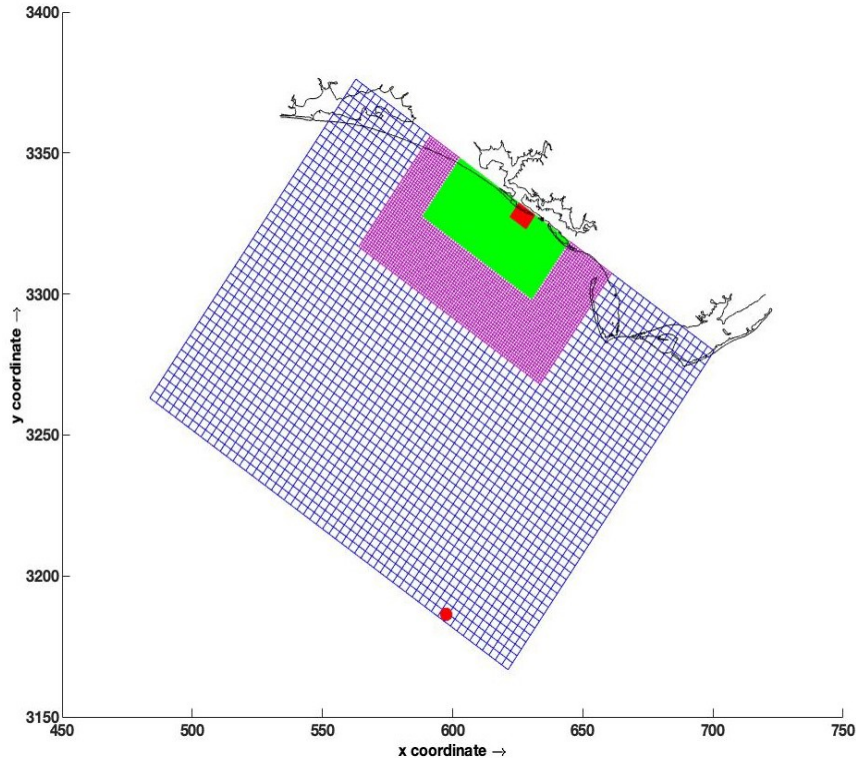


Figure 11. Multiple grids of the Delft3D wave module implemented in the TRES13 area with the red dot indicating the buoy 42039 location (from Santos Pessanha, 2019).

The NOAA’s buoy station 42039 (NOAA/NDBC 2019) is located within the wave domain’s area, but, initially, it was not used to set up the wave boundary conditions due to lack of wave direction data during the simulation period. Instead, the wave forcing boundary **condition was** set up using data from the NOAA Wavewatch III Gulf of Mexico and Northwest Atlantic model results (NOAA/NCEP 2019).

2.3.3. Morphology

Delft3D-MOR works in an integrated way with the wave and flow modules in a cycle. This system is a process-based model that considers the impact of the wave, currents, and sediment transport on morphological changes. Delft3D-Flow and Delft3D-Wave provide the hydrodynamic input to Delft3D-MOR, which updates the bathymetry considering the sediment transport field. In its turn, the bathymetry feeds back to the flow and wave modules, and the loop restarts.

Bedload transport occurs due to saltation and rolling within a thin layer over the seafloor. This kind of transport is directly caused by the energy from the flow. In the bedload theory, the

sediment starts to move when the forces promoting movement (e.g., fluid drag and lift force due to pressure gradient) are more significant than the forces hindering movement (e.g., gravity and friction). The kinetic energy transferred from the water to the grains is governed by the fluid's mass and flow velocity. In this context, the critical velocity (u^*) is defined as the flow velocity necessary to move a particle of a particular dimension and density. The critical velocity is essential to compute the critical bed shear stress ($\tau_{b,cr}$), which is used to solve the critical Shields criterion (θ_{cr}).

The Shields criterion (Shields 1936) is used to determine the beginning of sediment motion in a fluid. This parameter defines the greatest grain size (D) that can be moved by a flow velocity u , and it is estimated as

$$\theta_{cr} = \frac{\tau_{b,cr}}{[(\rho_s - \rho)gD_{50}]} \quad (35)$$

where ρ_s corresponds to the sediment density, ρ is the water density, g denotes gravity, and D_{50} is the mean diameter of the particle.

Delft3D uses the following estimation method of Van Rijn et al. (2003) to calculate the bedload transport (S_b)

$$|S_b| = 0.006\rho_s\omega_s D_{50}^{(l)} M^{0.5} M_e^{0.7} \quad (36)$$

where ω_s is the settling velocity, l denotes the sediment fraction, M is sediment mobility number cause by currents and waves, and M_e is excess sediment mobility number. The sediment mobility number (equivalent to the Shields parameter) is derived by the equation

$$M = \frac{v_{eff}^2}{(s-1)gD_{50}} \quad (37)$$

considering that s is relative density of sediment fraction (ρ_s / ρ) and v_{eff} signifies an effective velocity cause by currents and waves. The excess sediment mobility number can be calculated by the equation

$$M_e = \frac{(v_{eff} - v_{cr})^2}{(s-1)gD_{50}} \quad (38)$$

in which v_{cr} is critical barotropic velocity for the starting movement (parameter from Shields' theory). The effective velocity can be computed by the equation

$$v_{eff} = \sqrt{v_R^2 + U_{br}^2}$$

where v_R is the barotropic velocity in the bottom boundary layer and U_{br} is the bottom wave orbital velocities caused by the short waves.

3. Results and Discussion

The research has been conducted smoothly as planned. The results are presented in the three aspects: data analysis, 6-DoF model, and seabed environment model.

3.1. Observational Data Analysis

Most information in this section can be found in Chu et al. (2020). The currents and waves data were measured from the Nortek AWAC with frequency of 1 MHz installed at top of shallow and deep quadpods (one for each) from 21 April to 23 May 2013. The height of quadpod is 3 m. The temporal resolution is 1 minute for the current velocity vector data ($\mathbf{V}_w$), and 30 minutes for the wave characteristics data such as peak-period (T_p), significant wave height (H_s), and mean water level (MWL), which were obtained from processing original data with 2 Hz temporal resolution for 20 minutes every half hour. The water depth (h) is to add the heights of shallow (2.3 m) and deep (3.3 m) quadpods to the MWL. Bottom wave orbital velocity (U_{br}) is computed using the wave data (T_p , H_s , h) and the MATLAB function (Wiberg and Sherwood 2008) on the base of Eqs.(19)-(21a) [i.e., using the JONSWAP spectrum], sediment density (ρ_s), and medium grain size (d_{50}] [see Eq.(26)]. In turn the sediment Shields parameter (θ_{sed}), and equilibrium object percentage burial ($p_{B,eq}$) are calculated using Eq.(17) and Eq.(23) with coefficients $a_1 = 1.6$, $a_2 = 0.85$, $a_3 = 0$. These data are represented in Figure12 for the shallow quadpod and in Figure 13 for the deep quadpod.

Figure 12. Time series of (a) meridional current u_e (m/s), (b) latitudinal current u_n (m/s), (c) water depth h (m) (mean water level plus quadpod ‘s height, 2.3 m), (d) peak period T_p (s), (e) significant wave height H_s (m), (f) bottom wave orbital velocity U_{br} (m/s), and (g) sediment Shields parameter θ_{sed} from the shallow quadpod from 21 April to 23 May 2013 (from Chu et al. 2020).

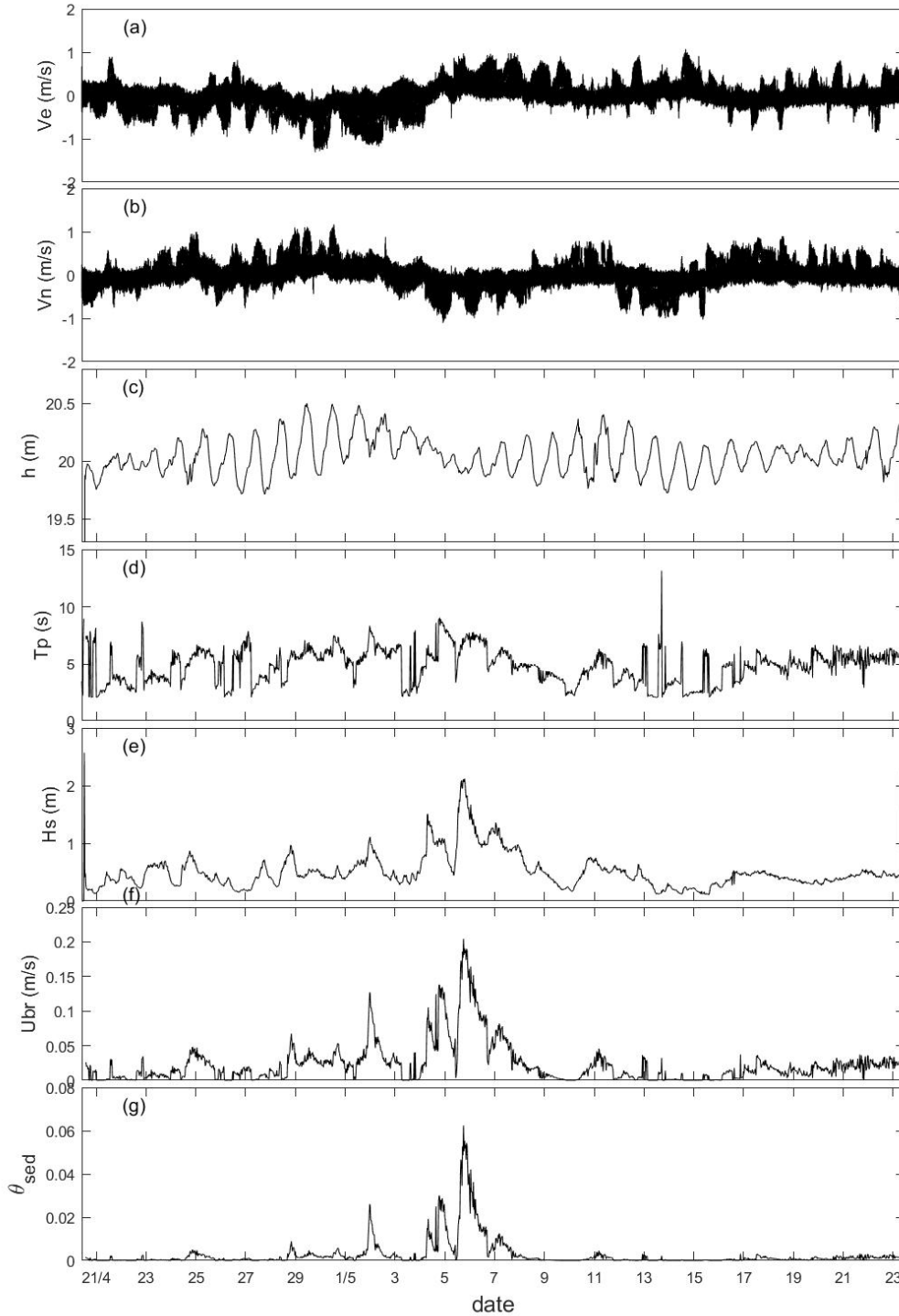


Figure 13. Time series of (a) meridional current u_e (m/s), (b) latitudinal current u_n (m/s), (c) water depth h (m) (mean water level plus quadpod ‘s height, 2.3 m), (d) peak period T_P (s), (e) significant wave height H_S (m), (f) bottom wave orbital velocity U_{br} (m/s), and (g) sediment Shields parameter θ_{sed} from the deep quadpod from 21 April to 23 May 2013 (from Chu et al. 2020).

3.2. 6-DoF Model Prediction on Munitions' Mobility and Burial

Most information in this section can be found in Chu et al. (2020). Munitions mobility and burial were predicted using this 6-DoF model consisting of Eqs.(25), (26), (28)-(34). The high-resolution environmental data (Figures 12 and 13) are used as model input.

3.2.1. Model Integration

The model was integrated for each surrogate (or replica) from the initial conditions (shown in Figure 4) on 12:40 (local time) 20 April to 23 May 2013 for both shallow and deep quadpods. For each surrogate or replica deployed in the shallow or deep quadpod, the angle between the current velocity vector $\mathbf{V}_w = (u_e, u_n)$ (data represented in Figures 12a,b or 13a,b) and the direction perpendicular to the main axis of cylinder is determined. The velocity vector $\mathbf{V}_w$ is then decomposed into $\mathbf{V}_w = (U, V)$ with U the perpendicular component, and V the paralleling component. The component U is used in the model. The object physical parameters such as the diameter (D), volume (used to determine length), mass per unit length (M), and rolling moment (I_0) are obtained from Table 1. The environmental data such as water depth (h), wave peak period (T_p), significant wave height (H_s), bottom wave orbital velocity (U_{br}) (shown in Figures 12 and 13), and sediment characteristics [Eq.(26)] are used for the scour model, i.e., Eqs(31)-(33) to get the burial percentage $p_B(t_k)$, and in turn the relative rolling center depth $p_b(t_k)$ using Eq.(34). With the object physical parameters (D, S_o, M, I_0), calculated $p_b(t_k)$, and observed (or modeled) bottom current velocity component perpendicular to the main axis of cylinder $U(t_k)$, the coefficients $[\alpha(t_k), \beta(t_k)]$ for the 6-DoF model [i.e., Eq.(25a, b)] are calculated using (23). Figure 14 shows the flow chart of the 6-DoF modeling.

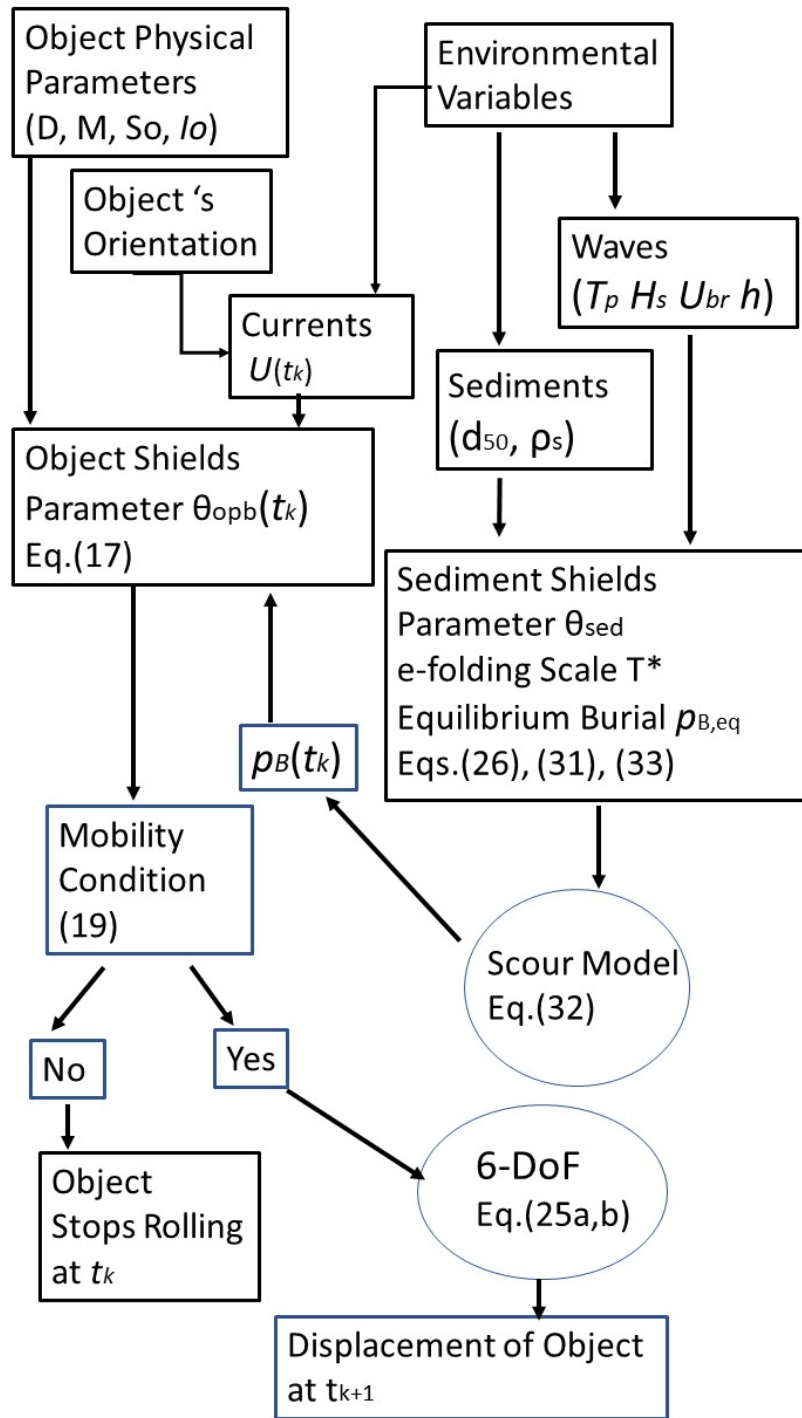


Figure 14. Flow chart of the 6-DoF model prediction (from Chu et al., 2020).

3.2.2. Model Verification

The model output includes the object Shields parameter $\theta_{opb}(t_k)$ at the shallow (deep) quadpod shown in Figure 15 (Figure 18), the object's displacement $l(t_k)$ at the shallow (deep) quadpod shown in Figure 16 (Figure 19), and the object's burial percentage $p_B(t_k)$ at the shallow (deep) quadpod shown in Figure 17 (Figure 20). The two dotted-dashed lines for each panel in Figures 15-20 show the period of detection when the surrogate (or replica) positions were tracked by the sector scanning sonar images. The red color in Figures 15 and 18 shows that the condition for rolling the object [Eq.(19)] is satisfied. This condition can be approximately as $\theta_{opb} > 1$. The time periods with the red colored θ_{opb} in Figure 15 (Figure 18) correspond well to the objects' displacements in Figure 16 (Figure 19). Several objects were motionless during their detection periods such as C2, C4, C6, D3, and D6 at the shallow quadpod, and D5 in the deep quadpod. Their Shields parameters are less than one ($\theta_{opb} < 1$) (see Figure 15 for the shallow quadpod and Figure 18 for the deep quadpod). The solid Delrin A1 had very large θ_{opb} values at the deep quadpod (see the upmost panel in Figure 18), it displaced largest distance among all the objects at the deep quadpod (Figure 19). The burial percentages p_B for all the objects were less than 0.5 in the shallow quadpod except during the storm event on 5-6 May 2013 (Figure 17). However, the burial percentages p_B for all the objects were less than 0.25 in the deep quadpod even during the storm event on 5-6 May 2013 (Figure 20). From Figure 16 (Figure 19) for object displacements at the shallow (deep) quadpod and their initial locations (Figure 3), the predicted locations of all objects during their detection periods are presented in Figure 21a for the shallow quadpod and Figure 21b in the deep quadpod.

On the other hand, munitions mobility and burial were observed by divers and sector scanning sonar images during the field experiment. A total of 8 munitions buried in place at the shallow quadpod location were recovered by divers during the maintenance dive performed on 8 May 2013 (Figure 3b). However, none of the replica munitions were recovered at the deep quadpod location. Note the munitions excavated by the divers at the shallow quadpod location on 8 May 2013 were immediately redeployed for the duration of the experiment as shown in Figure 3b. An overview of the observed munitions mobility throughout the deployment is shown for both the shallow (Figure 21c) and deep (Figure 21d) quadpod locations, determined from sector scanning sonar images. Based on the known initial locations during the deployment, the objects were identified and plotted when their locations shifted or they were not visible between successive sector scanning sonar images. Table 3 shows the comparison between model predicted and observed objects' mobility for both shallow and deep quadpods. Along with the comparison between Figure 21a and Figure 21c, Figure 21b and Figure 21d, this 6-DoF model has capability to predict the objects' mobility.

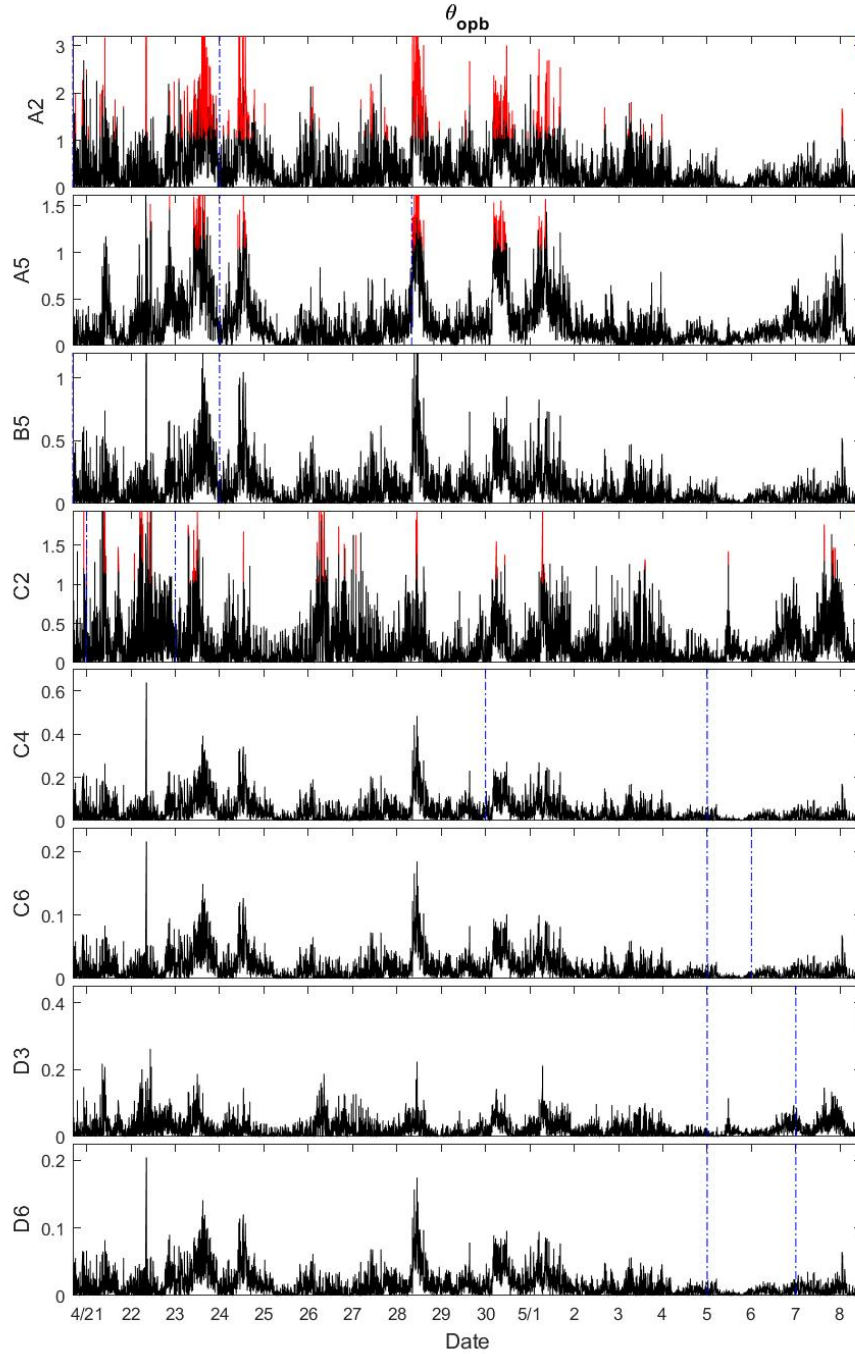


Figure 15. 6-DoF Model predicted object Shields parameter θ_{opb} for each surrogate (or replica) at the shallow quadpod from 21 April to 8 May 2013. The two dotted-dashed lines for each panel show the period of detection when the positions of surrogate (or replica) were tracked by the sector scanning sonar images. The red color shows that the condition for rolling the object [Eq.(19)] is satisfied (from Chu et al., 2020).

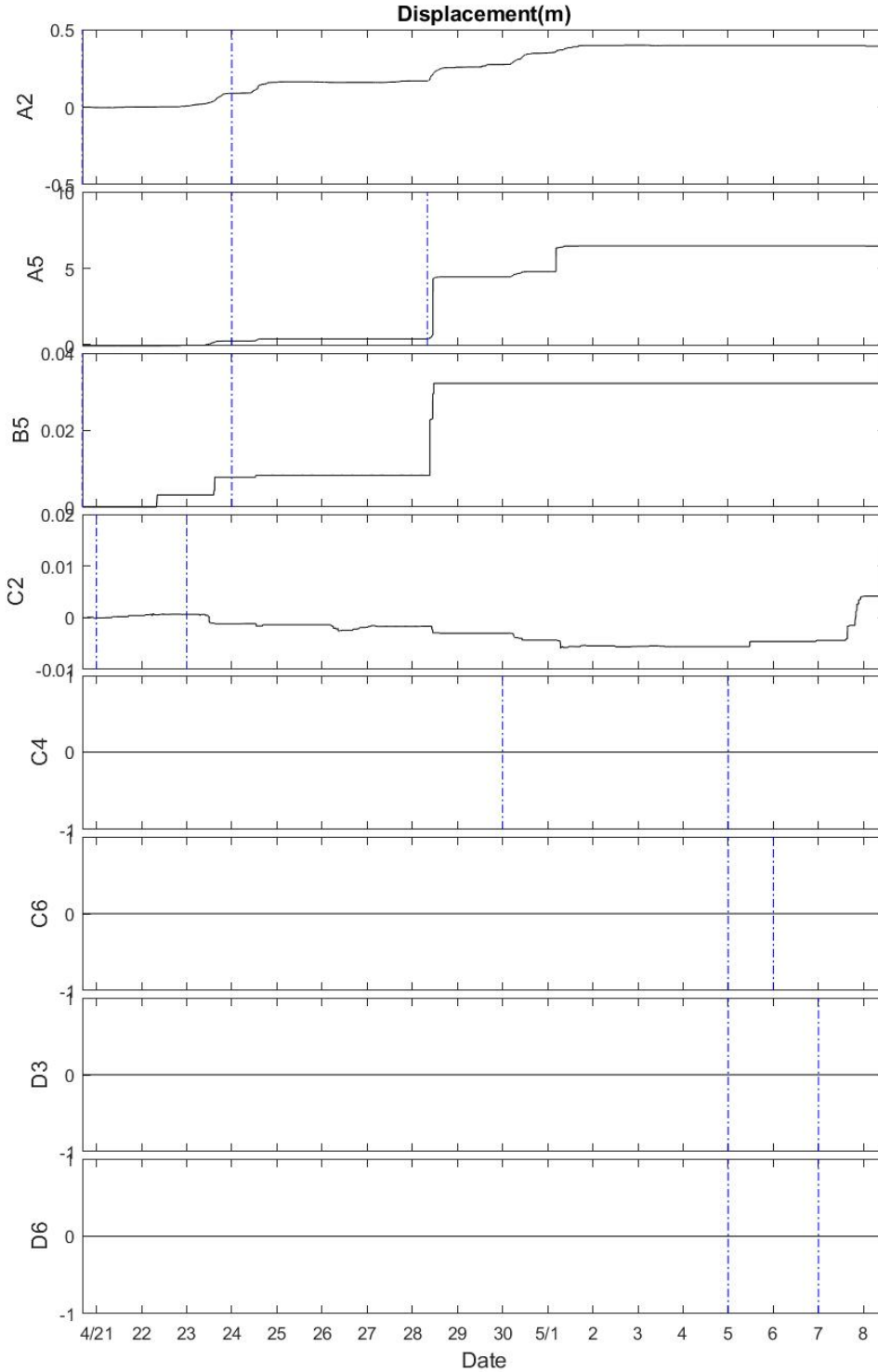


Figure 16. 6-DoF Model predicted displacement $l(t)$ for each surrogate (or replica) at the shallow quadpod from 21 April to 8 May 2013. The two dotted-dashed lines for each panel show the period of detection when the positions of surrogate (or replica) were tracked by the sector scanning sonar images (from Chu et al., 2020).

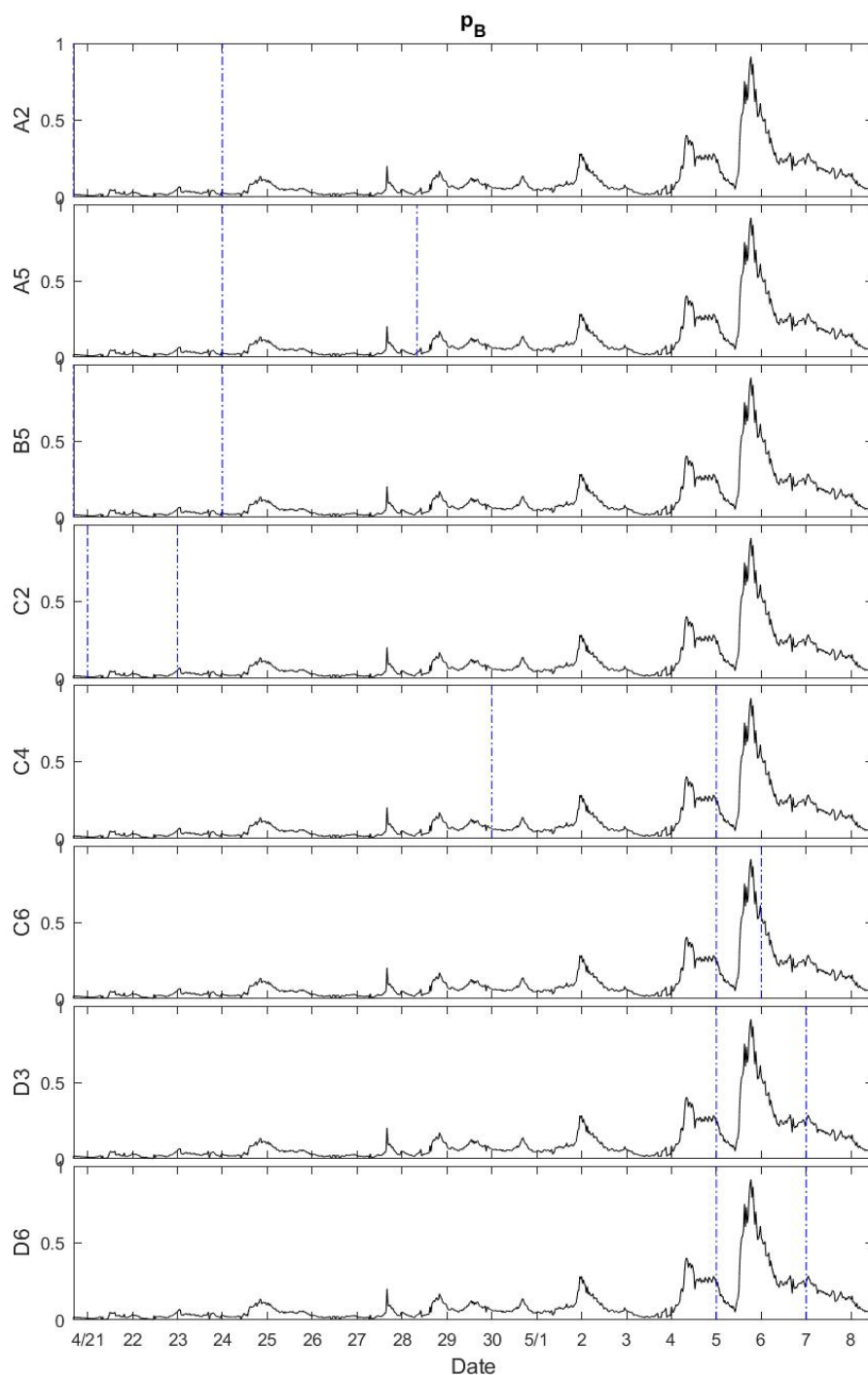


Figure 17. 6-DoF Model predicted burial percentage $p_B(t)$ for each surrogate (or replica) at the shallow quadpod from 21 April to 8 May 2013. The two dotted-dashed lines for each panel show the period of detection when the positions of surrogate (or replica) were tracked by the sector scanning sonar images (from Chu et al., 2020).

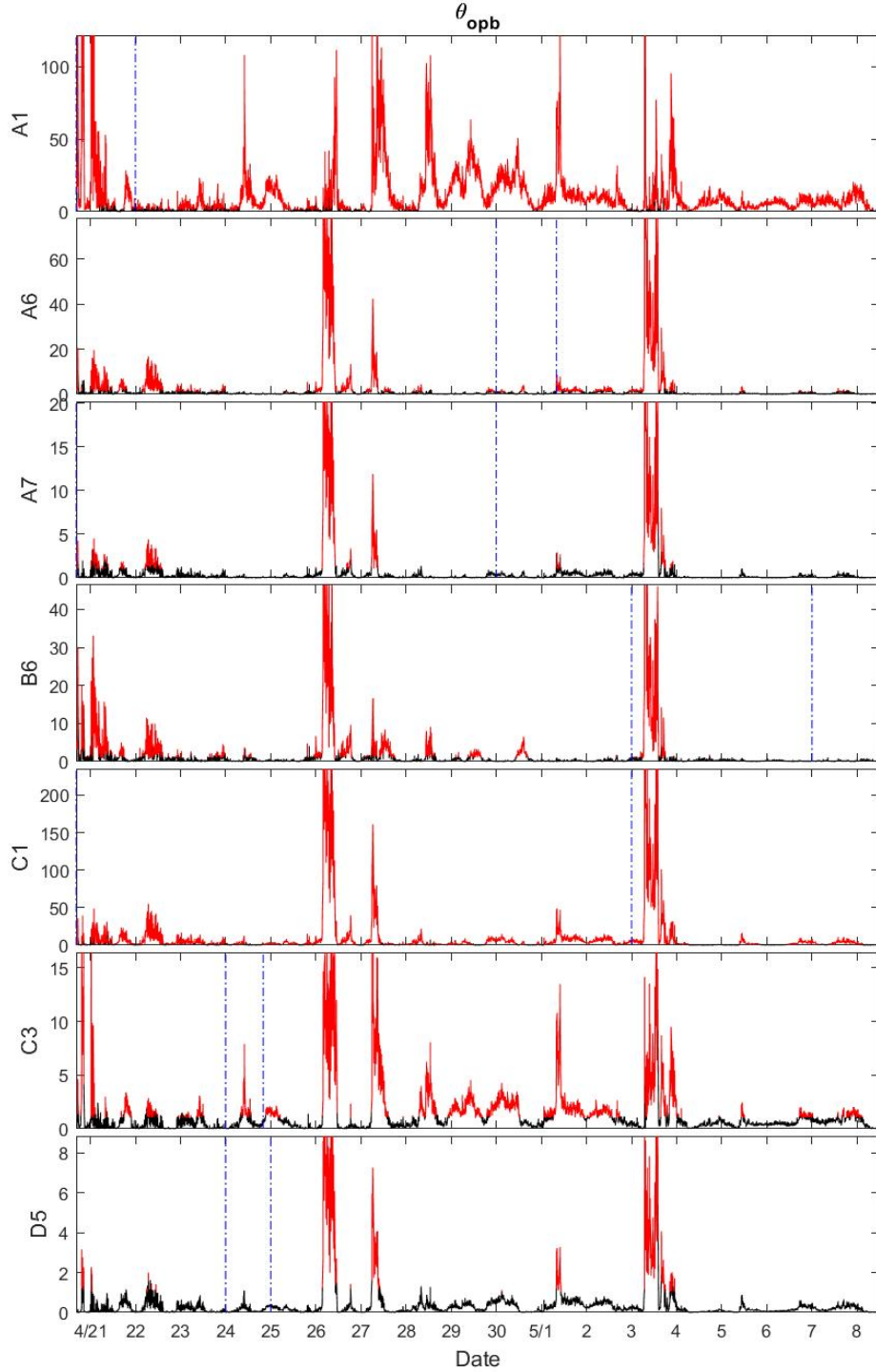


Figure 18. 6-DoF Model predicted object Shields parameter θ_{opb} for each surrogate (or replica) at the deep quadpod from 21 April to 8 May 2013. The two dotted-dashed lines for each panel show the period of detection when the positions of surrogate (or replica) were tracked by the sector scanning sonar images. The red color shows that the condition for rolling the object [Eq.(19)] is satisfied (from Chu et al., 2020).

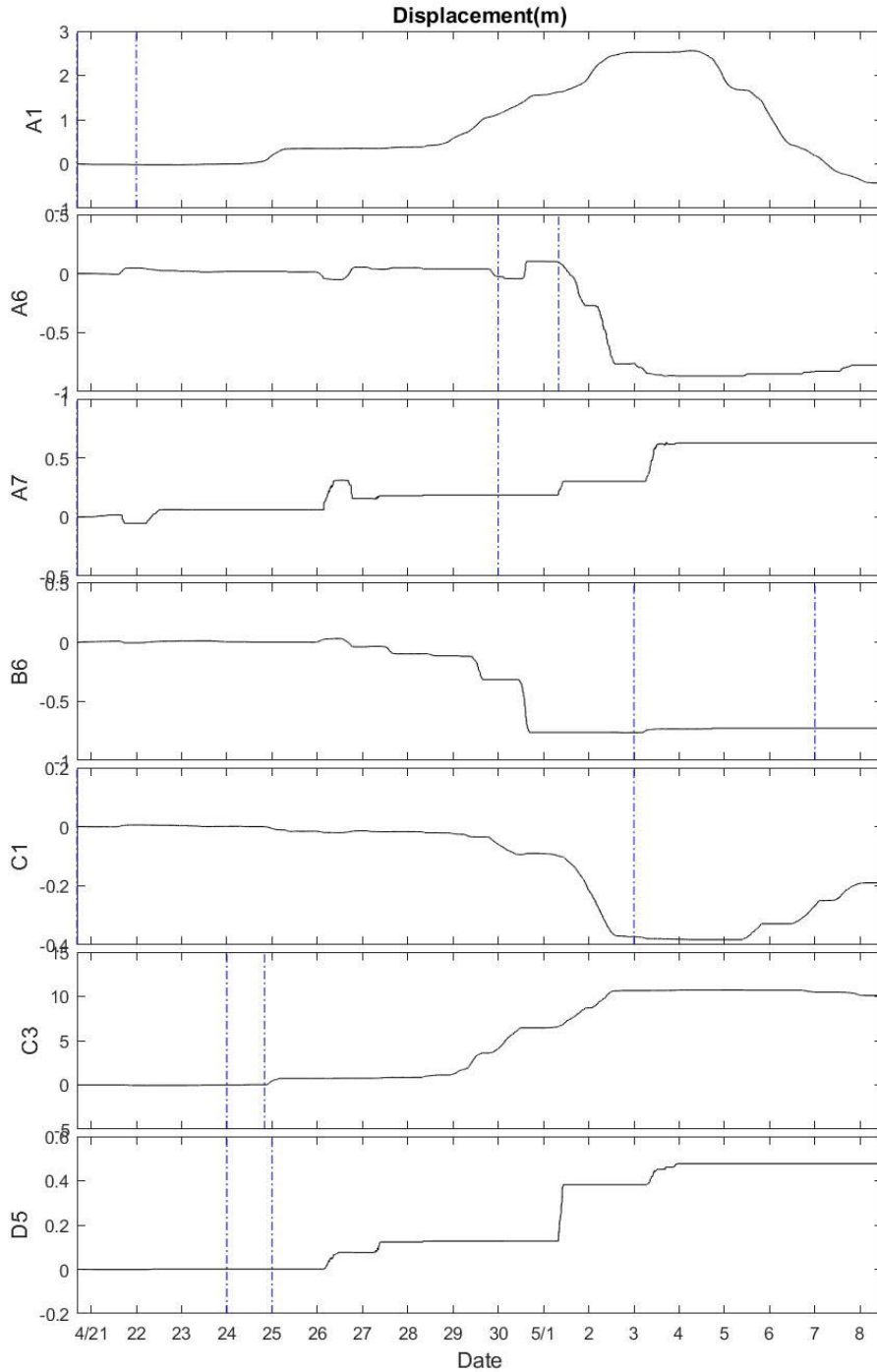


Figure 19. 6-DoF Model predicted displacement $l(t)$ for each surrogate (or replica) at the deep quadpod from 21 April to 8 May 2013. The two dotted-dashed lines for each panel show the period of detection when the positions of surrogate (or replica) were tracked by the sector scanning sonar images (from Chu et al. 2020).

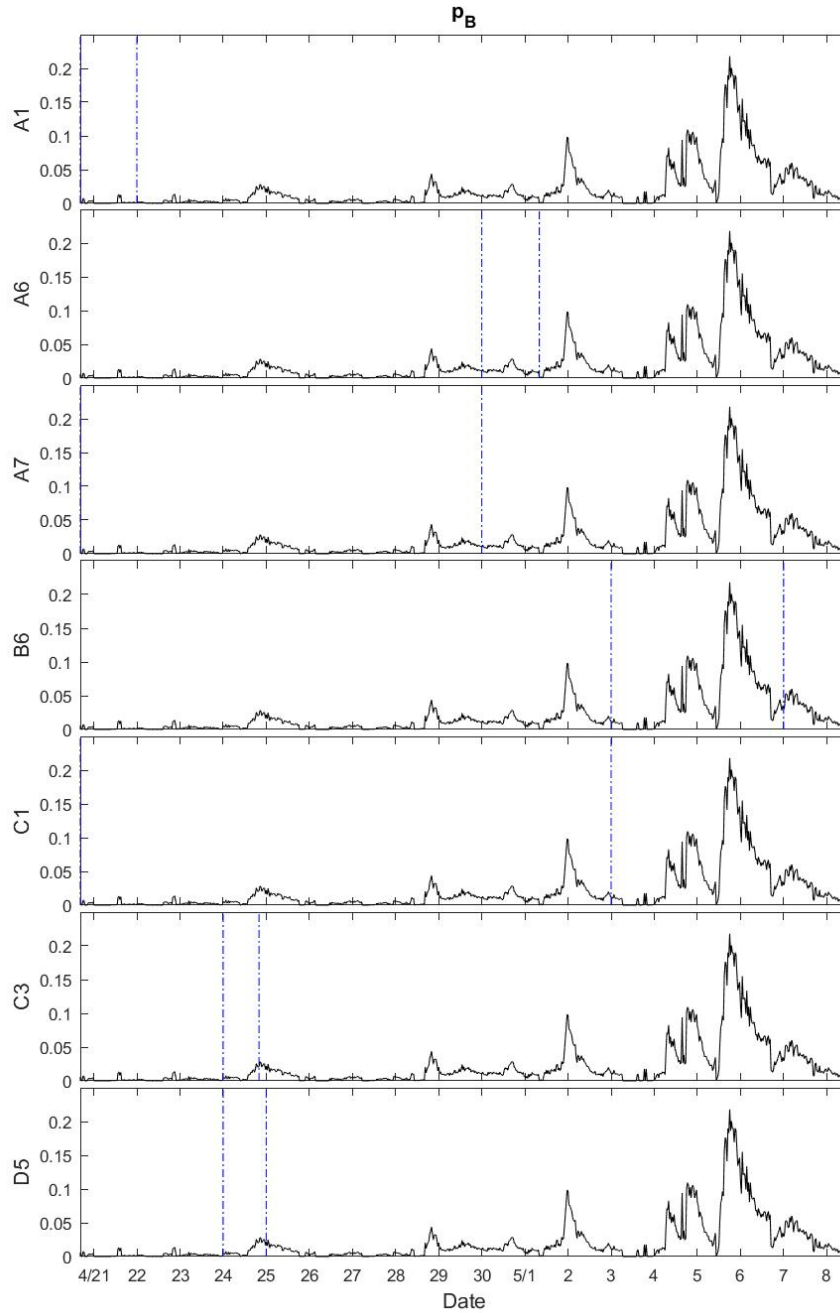


Figure 20. 6-DoF Model predicted burial percentage $p_B(t)$ for each surrogate (or replica) at the shallow quadpod from 21 April to 8 May 2013. The two dotted-dashed lines for each panel show the period of detection when the positions of surrogate (or replica) were tracked by the sector scanning sonar images (from Chu et al., 2020).

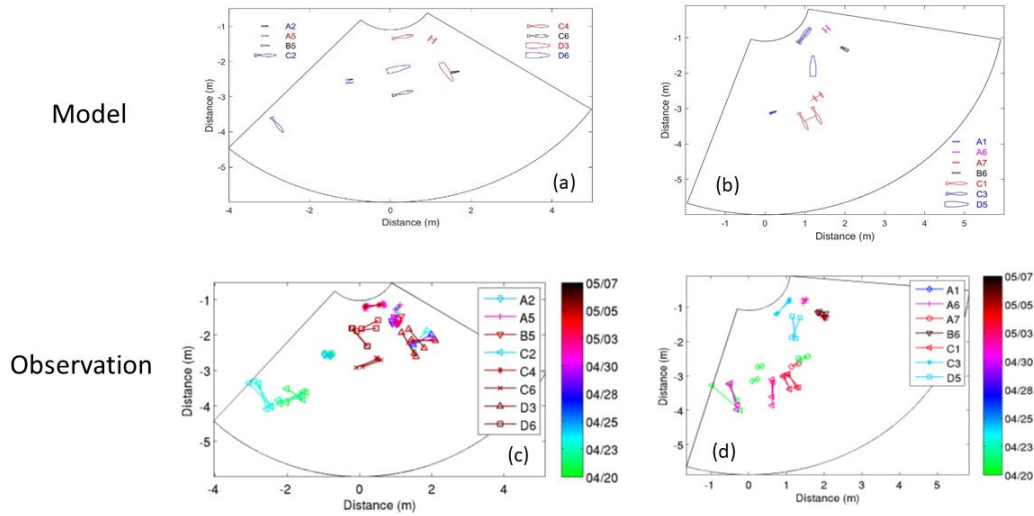


Figure 21. Comparison between model-predicted and observed objects' mobility: (a) model prediction at the shallow quadpod, (b) model prediction at the deep quadpod, (c) observation at the shallow quadpod, and (d) observation at the deep quadpod. Note that Figures 21c and 21d were copied from Calantoni et al. (2014). The observed positions of surrogate (or replica) were tracked by the sector scanning sonar images during the period of detection (see Table 5).

Table 5. Comparison of modeled and observed mobility (i.e. absolute value of displacement of the center of mass) for surrogates (or replica) at both shallow and deep quadpods (from Chu et al. 2020).

Shallow Quadpod				Deep Quadpod			
Munition	Period of Detection	6-DoF (m)	Obs (m)	Munition	Period of Detection	6-DoF (m)	Obs (m)
A2	4/20-23	0.09	0.1	A1	4/20-22	0.02	0.5
A5	4/24-5/03	0.14	0.1	A6	4/30-5/01	0.12	0.2
B5	4/20-24	0.1	0.2	A7	4/20-30	0.19	0.3
C2	4/21-23	0.0	0.1	B6	5/3-7	0.04	0.0
C4	5/03-07	0.0	0.0	C1	4/20-5/3	0.37	0.4
C6	5/05	0.0	0.0	C3	4/24	0.05	0.0
D3	4/24-5/05	0.0	0.0	D5	4/24	0.0	0.1
D6	5/05-07	0.0	0.2				

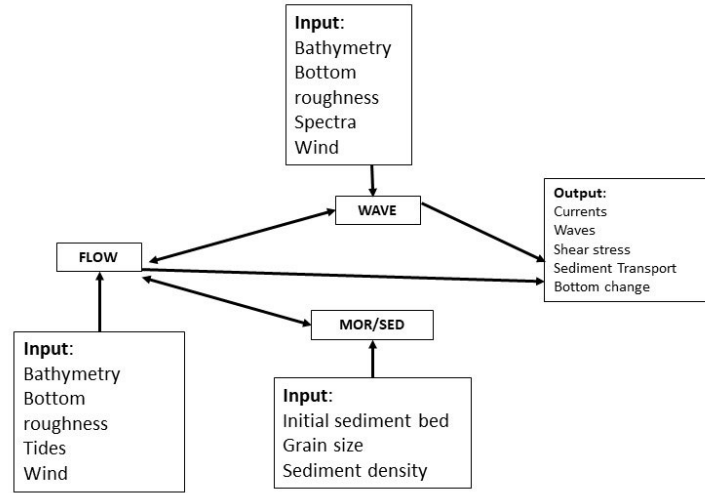
3.3. Seabed Environmental Prediction

Most information in this section can be found in Santos Pessanha (2019). The implemented Delft3D model predicts the water level, waves, currents, and morphological changes during the period from April 21 and May 13, 2013. The flow chart of this model is illustrated in Figure 22.

Environmental Modeling (Delft3D)

Modules:

- Flow
- Wave
- Morphology



1

Figure 22. Flow chart of seabed environmental modeling (from Santos Pessanha, 2019).

The model performance was evaluated by relative mean absolute error (RMAE), root-mean-squared error (RMSE), bias, and model skill (Wilmott,1981),

$$Skill = 1 - \frac{\sum |X_{mod} - X_{obs}|^2}{\sum \left(|X_{mod} - \overline{X_{obs}}| + |X_{obs} - \overline{X_{obs}}| \right)^2} \quad (39)$$

where X is the variable of interest (e.g., water level and significant wave height), $\overline{X}$ is the time mean, the subscript *mod* denotes model output, and the subscript *obs* signifies observations. A perfect agreement between model output and observations results in a skill equal to one. In contrast, complete disagreement implies a skill equal to zero.

3.3.1. Water Level

The model achieved an excellent performance simulating water level. The skill at Panama City Beach tide station is 0.987, the bias is 0.014 m, and the RMSE is 0.031 m. Figure 23 shows the model output and observations.

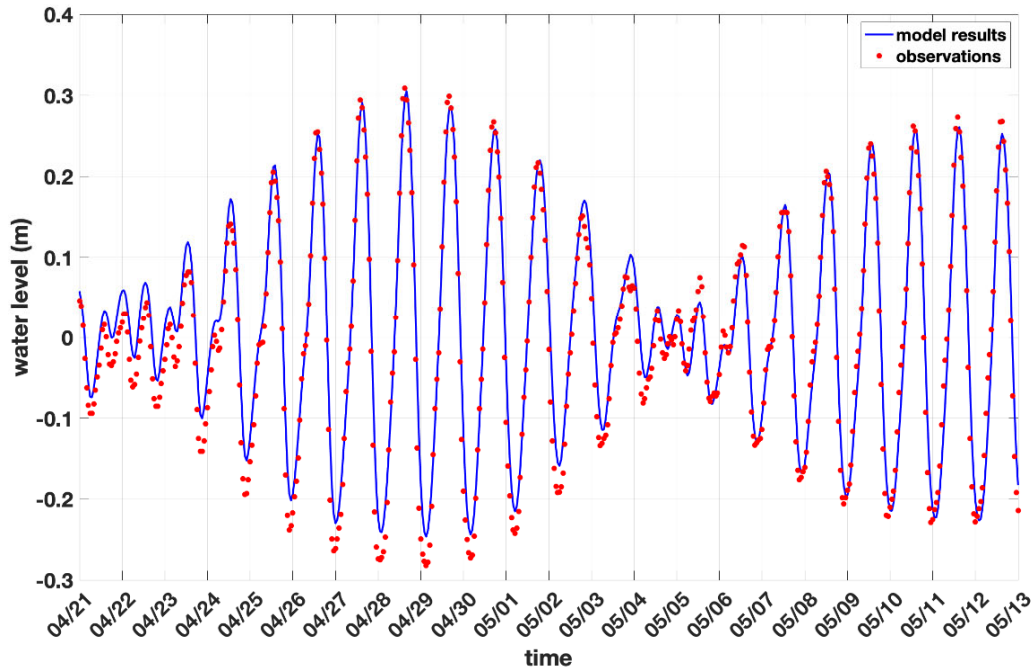


Figure 23. Observed (red dots) and predicted (blue curve) water level (from Santos Pessanha, 2019).

3.3.2. Significant Wave Height, Wave Direction, and Peak Period

The significant wave height (H_s) and mean direction (θ) were well represented most of the time by the model in both shallow and deep quadpods' locations. The model was able to represent the variation pattern of the wave peak period (T_p), but it underestimated the values along almost the whole simulation as illustrated in Figures 24 and 25. At the shallow quadpod, the skill is 0.896, the bias is -0.031 m, the RMAE is 0.8, and the RMSE is 0.166 m for significant wave height. At the deep quadpod, the skill is 0.888, the bias is -0.004 m, RMAE is 0.072, and the RMSE is 0.2 m for significant wave height.

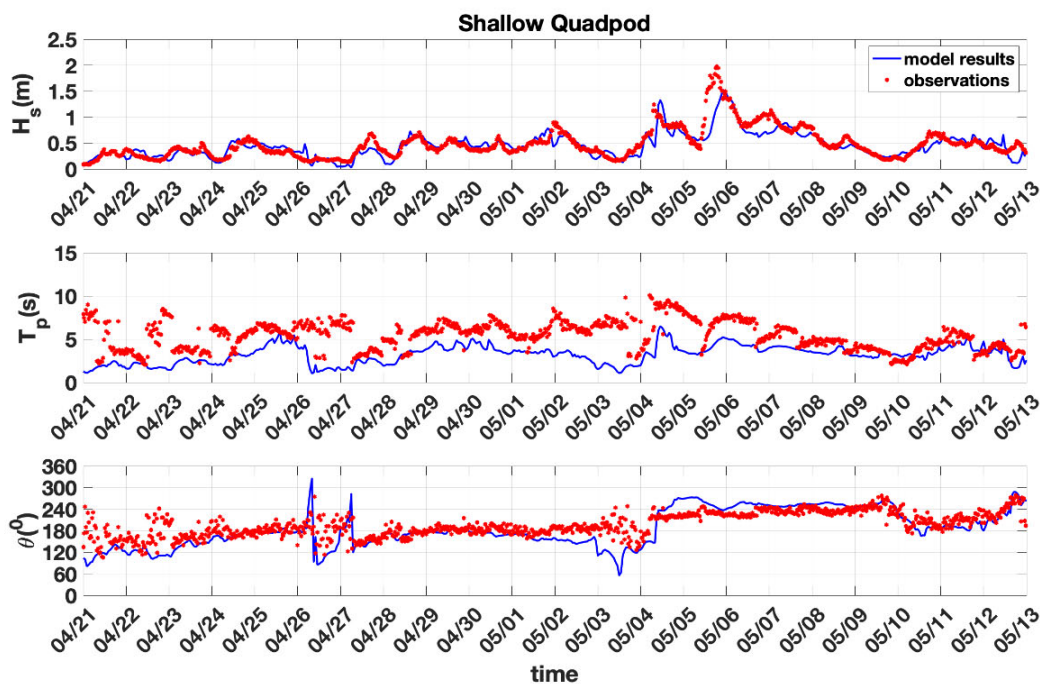


Figure 24. Observed (red dots) and predicted (blue curve) wave characteristics at the shallow quadpod location (from Santos Pessanha, 2019).

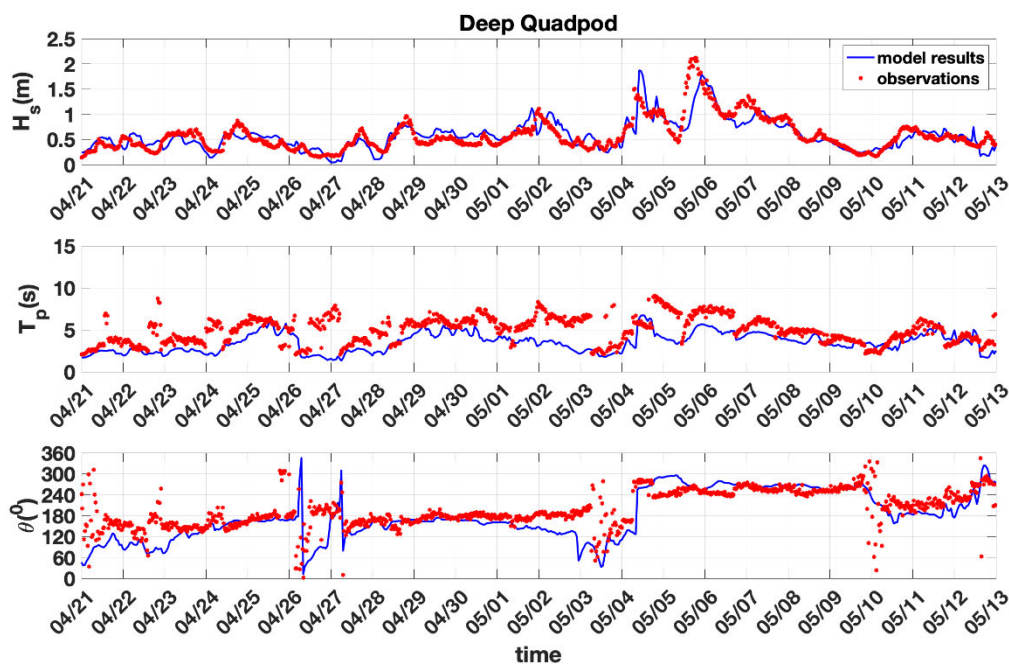


Figure 25. Observed (red dots) and predicted (blue curve) wave characteristics at the deep quadpod location (from Santos Pessanha, 2019).

3.3.3. Current Speed and Direction

Especially in the shallow quadpod's location, the model was able to depict well the predominantly longshore current direction. Also, the model was able to represent the pattern of the variation of current speed satisfactorily, but it had difficulties in describing the intensity accurately as showed in Figures 26 and 27. At the shallow quadpod, the skill is 0.479, the bias is -0.047 m, RMAE is 0.497, and the RMSE is 0.078 m. At the deep quadpod, the skill is 0.508, the bias is -0.019 m, RMAE is 0.454, and the RMSE is 0.077 m.

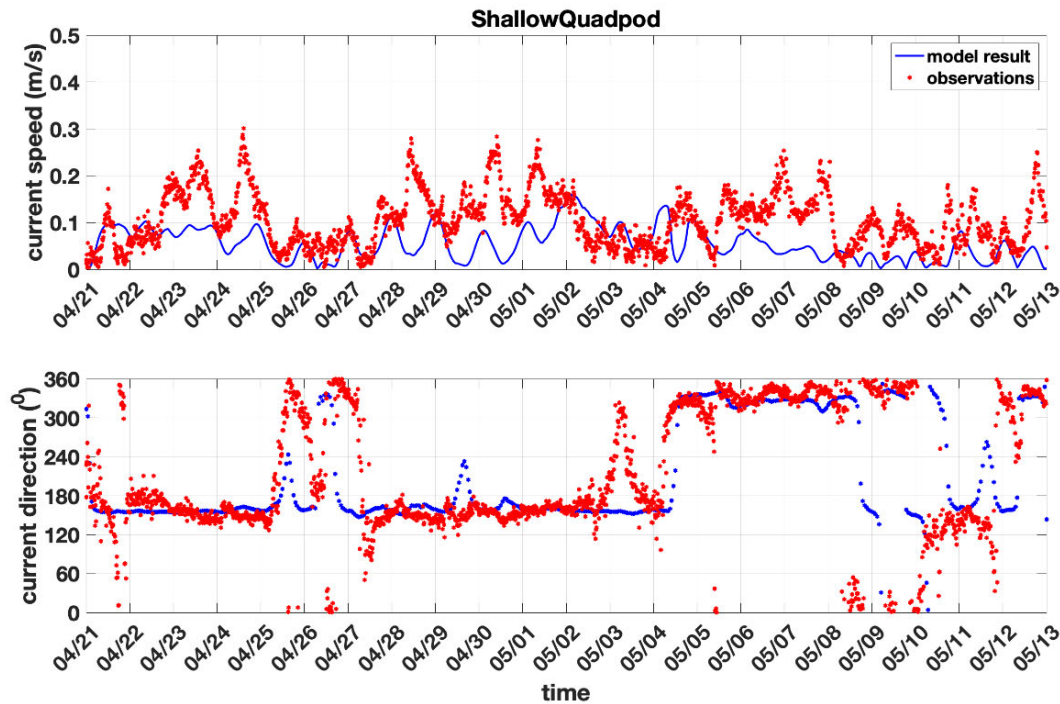


Figure 26. Observed (red dots) and predicted (blue curve) current speed and direction at the shallow quadpod location (from Santos Pessanha, 2019).

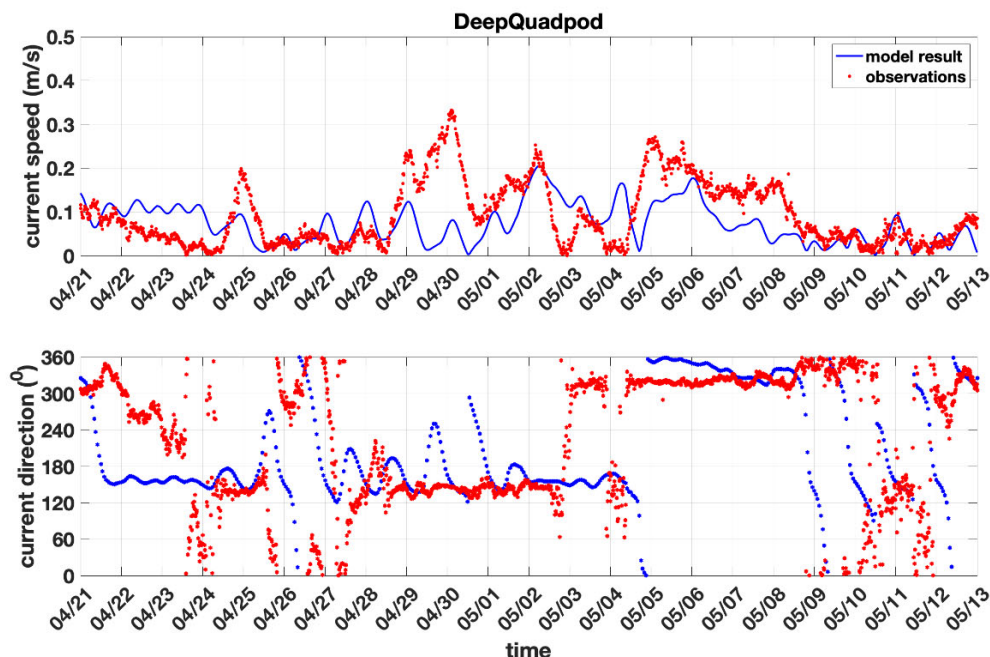


Figure 27. Observed (red dots) and predicted (blue curve) current speed and direction at the deep quadpod location (from Santos Pessanha, 2019).

3.3.4. *Sediment Accretion*

According to Calantoni et al. (2014), no bottom variations were measured in the deep quadpod's location during the storm event that occurred in the TREX13 experiment. Significant modifications in the seabed just happened in the shallow quadpod. Thus, the focus of this section is the model output regarding the shallow quadpod's location. Figure 28 presents the observed and modeled predicted sediment accretion at shallow quadpod. Measurements show a deposit of 0.15 m of sand after the storm in the period between May 4 and 8. Considering that observations have a high spatial and temporal resolution, the model did a good job representing the quick increase of sediment and also the amount of deposited sand at the end of the period. The graph also shows the **sensitivity** of the model regarding grain size. Considering that more than 79% of the particles collected during the TREX13 experiment are classified as fine sand (Calantoni, 2014), the model was tested for different particle size distribution D_{50} : 125 μm , 150 μm , and 200 μm . As expected, the smallest grain size ($D_{50}=125\mu\text{m}$) gave the most significant accretion of sand.

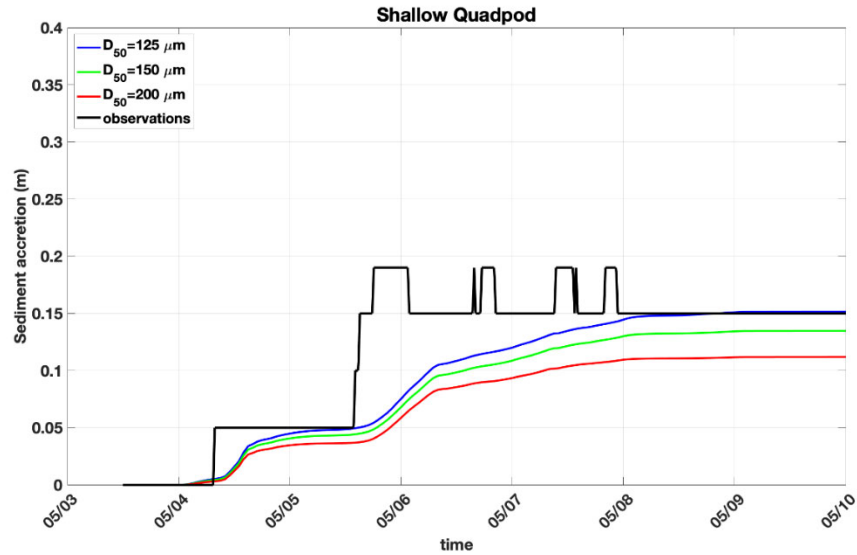


Figure 28. Observed and model predicted (with different grain sizes) sediment accretion at shallow quadpod location with the blue, green, and red curves representing the model output for different particle size distribution (from Santos Pessanha, 2019). The black curve was obtained from TREX13 representing the sediment accretion from maximum backscatter intensity (from Calatoni et al. 2014).

Figure 29 shows the deposit of sediment in the area of interest on May 8. The shallow quadpod's location is in the 0.15 m range (green color) of accretion of sediment and the deep quadpod is in a location of zero sedimentation (blue color), which agrees with observations.

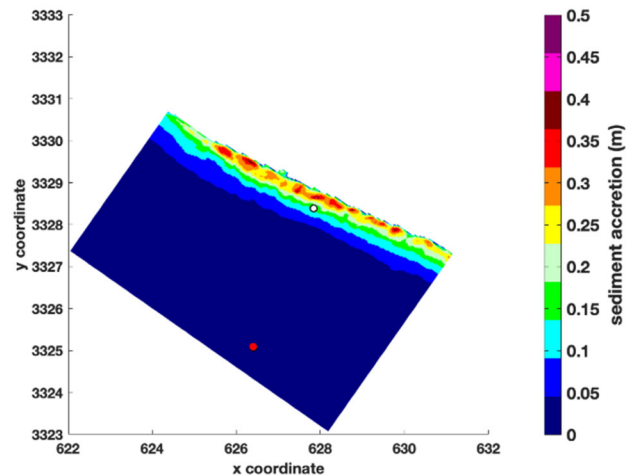


Figure 29. Predicted sediment accretion after the storm event on May 8 at 08Z with 0.15 m of sediment accretion at the shallow quadpod and no sediment accretion at the deep quadpod (from Santos Pessanha, 2019).

The model's capacity is verified using the Brier Skill Score (BSS) suggested by Van Rijn et al. (2003),

$$BSS = 1 - \left[\frac{\left\langle \left(|z_{b,c} - z_{b,m}| - \Delta z_{b,m} \right)^2 \right\rangle}{\left\langle \left(z_{b,0} - z_{b,m} \right)^2 \right\rangle} \right] \quad (40)$$

where $z_{b,c}$ denotes the computed bed level, $z_{b,m}$ is the measured bed level $z_{b,0}$ signifies initial bed level, and $\Delta z_{b,m}$ is the uncertainty of measured bed level. Table 6 presents the model performance's qualification according to Van Rijn et al. (2003) based on the BSS. Table 7 presents the BSS for the model prediction with different particle size characteristics.

Table 6. *Metrics for quality of morphological prediction* by Van Rijn et al. (2013).

Qualification	BSS
Excellent	1.0-0.8
Good	0.8-0.6
Reasonable/fair	0.6-0.3
Poor	0.3-0
Bad	<0

Table 7. Statistics for the quality of Delft3D morphological prediction (from Santos Pessanha, 2019).

D ₅₀	BSS	Qualification
125μm	0.8518	Excellent
150μm	0.8121	Excellent
200μm	0.7446	Good

4. Summary and Ongoing Analysis

The following points summarize this report.

(1) The 6-DoF model was recently developed to predict underwater cylindrical objects' mobility and burial in sandy bed, based on the results from SERDP sponsored projects such as MR-2224, MR-2227, MR-2319, and MR-2320, and ONR sponsored mine burial project. Rolling of the object is the major dynamics of this model with a new concept of its rolling center in the sediment. The

displacement of object caused by rolling satisfies the Riccati equation with analytical solution. Along with the dynamical model, the empirical scour model [13] is used as part of the prediction system.

(2) Data collected during TREX13 off the coast of Panama City, Florida at shallow and deep quadpods from 21 April to 23 May 2013 from the SERDP project MR-2320 were used as model input or model verification depending on the data type. The environmental data such as bottom currents, water depth (h), peak period (T_p), significant wave height (H_s), sediment density (ρ_s), and medium grain size (d_{50}) are taken as input to calculate the bottom wave orbital velocity U_{br} and sediment Shields parameter θ_{sed} , and in turn the burial percentage p_B and the sediment depth percentage (p_b). The physical characteristics data of an object such as diameter (D), relative density (S_o), mass (M), and rolling moment (I_o) are taken as input to the 6-DoF model. The objects' positions tracked by the sector scanning sonar images are used for model evaluation. The predicted objects' positions agree quite well with the observed surrogates (or replicas) data.

(3) The 6-DoF mode developed in this study is only for cylindrical objects. Also, it only considers the roll of the cylinder around its major axis. The model ignores pitch and yaw. It is necessary to extend the modeling effort to more realistic shapes and more complete motion for operational use.

(4) Although the Delft3D version 4.0.01 implemented to the TREX13 area has capability to predict nearshore water level, currents, waves, and morphological change, the bathymetric data we used came from several surveys whose most recent was 2010, three years before the TREX13 experiment. The bathymetry of the beginning and end of the experiment period would be very useful to calibrate and evaluate the model performance more precisely. The wind data used as input for the model has a resolution of 28 km, which may not be the most appropriate one. It can impact the hydrodynamic results, mainly in waves and currents. Wave boundary conditions were set using the output from the Wavewatch III model. There is an NOAA buoy in the area of interest, but no data is available for the experiment period. The use of Wavewatch III rather than observations to set up the wave boundary conditions may impact the model accuracy.

(5) We continue to work closely with Dr. Calantoni (SERDP PI, MR19-1317) to get sufficient and reliable data in both seabed environment and munitions' mobility/burial through participating the field experiment planned in MR19-1317. The data will be used for model evaluation and verification. My PhD student (LCDR Santos Pessanha) will participate the field experiment scheduled in December 2020 by Dr. Calantoni with the SERDP Project MR19-1317.

We will also work closely with Dr. Rennie (SERDP PI, MR19-1126) to incorporate our effort into the Underwater Munitions Expert System (UnMES)

Products: We have presented our research at seven conferences. A paper on the 6-DoF model for predicting munitions' mobility and burial was submitted to the IEEE Journal of Oceanic

Engineering. A MS thesis entitled “Modeling of morphological responses to storm event during TREX13 experiment” was completed by LCDR Santos Pessenha (advised by Peter Chu) in December 2019. We have been working on a research paper from this thesis.

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