MOBILITY OF UNEXPLODED ORDNANCE
USING SPHERICAL SURROGATES
IN THE SWASH ZONE

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

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ABSTRACT

Predictive and probabilistic models require physical data to implement a practical procedure for monitoring and removing munitions or unexploded ordnance (UXO). Physical UXO response to wave forcing varies depending on the shape, location and density of a given munition. A laboratory experiment was conducted to study the mobility of spherical munition surrogates for cluster bombs (BLU61).

A dam-break mechanism was designed in the Center for Applied Coastal Research wave flume, generating repeatable swash events onto a mobile sand bed with median grain diameter of 0.31 mm and a slope of 1:7. A variety of sensors were deployed in the flume to monitor the produced hydrodynamics including a maximum water velocity ~ 1.5 m/s. A Velodyne laser system was used to monitor bed surface variability. A wide-angle field of view camera was deployed from overhead to track surrogate response in the form of displacement.

Four spherical munition surrogates were constructed to span a range of densities (specific gravity between 1.8 and 7.7). Surrogates were deployed in pairs at five different locations on the beach and at three different burial depths. Each scenario was repeated five times to determine a probabilistic response to repeatable forcing, determined by sensor data comparison for all runs. The beach was reshaped manually between subsequent runs, and a root-mean-square elevation error of less than 3 mm was maintained. Imagery from the overhead camera was converted to real world coordinates through a camera calibration and rectification. Cross-shore surrogate
trajectories were traced using a motion-based object tracking technique and validated through manual measurements.

A relationship between wave forcing, initial sphere location, initial burial depth and sphere density to sphere response (subsequent migration) was formed through parameterization and a dimensional analysis. An Object Mobility Number was identified for and compared to the total distance traveled determined from averaging five cross-shore trajectories (squared correlation coefficient of 0.65). Calculated mobility numbers increased with a decrease in density. Total travel distance decreased with an increased initial burial depth. Net onshore motion was not observed for any of the tested scenarios. Motion initiated upon uprush or backwash always resulted in a net offshore displacement.
Chapter 1

INTRODUCTION

1.1 Unexploded Ordnance and Munitions Response Program

Unexploded ordnance (UXO), also referred to as munitions, are known to contaminate thousands of sites in the United States both on land and in underwater environments (SERDP, 2010). A large amount of effort has been made in determining the quantity and classification of munitions known to exist at Formerly Used Defense Sites (FUDS) where preceding military training and testing activities have dispersed their presence. These classification projects, known as Geophysical Classification, allow regulators to gain familiarity with the hazardous status of FUDS in terms of public safety and remediation efforts. Identified munitions are then either removed, left in place, or blown up.

Many FUDS tend to be concentrated along the coast (Figure 1.1) and are subjected to a range of hydrodynamic forcing and morphodynamic variability. Data are lacking on how munitions mobilize and migrate, especially near the shoreline (the beach face) and in relation to varying coastal conditions. For instance, storms and subsequent beach evolution may exhume UXO and allow for cross-shore and/or alongshore UXO migration, increasing risk to the public. Sites deemed munitions-free may still be at risk of being re-populated through migration processes (Figure 1.2). Dredging of contaminated offshore borrow sites for beach nourishment projects can also lead to the distribution of munitions on the beach face.
The Department of Defense supports the Strategic Environmental Research and Development Program (SERDP) with one thrust area being a Munitions Response program. A key aspect of this program is the creation of a model that site managers can use for risk assessment. Researchers at the Johns Hopkins Applied Physics Laboratory have developed the Underwater Munitions Expert System (UnMES), that is built on a probabilistic Bayesian framework (Rennie et al., 2017). A probabilistic approach to solving coastal systems is often chosen when a deterministic model is unable to resolve first-order physics, such as turbulent induced processes and morphodynamic response. UnMES is embedded in a Geographic Information System (GIS) framework, giving site managers a decision support tool through the display of the spatial variation of existing munitions and their risk status (Rennie et al., 2015). Probability distributions output from UnMES provide key information such as areas of munition aggregation due to hydrodynamic conditions and munition classification. The classification of munitions response requires both laboratory and field data for further development into UnMES (Figure 1.3).

Figure 1.1: Formerly Used Defense Sites (SERDP, 2010).
Figure 1.2: Munition remnants scattered on beach face after a storm event (Pow, 2015).

Figure 1.3: Work-flow of Munitions Response program created by SERDP to characterize risk and plan for remediation efforts (Rennie et al., 2017).
1.2 Munition Mobility Research

Using surrogates to resemble munitions in laboratory and field settings is a contemporary approach for researchers to study object mobility in the nearshore. Research into the mobility of cobble-sized objects has been motivated by naval interests since these objects are of similar size and weight to anti-tank mines (Luccio et al., 1998, Voropayev et al., 2003, Rennie et al., 2007). Data for other shaped objects (cylinders and cones) also exist, mainly for conditions where objects are completely submerged and subject to oscillatory or steady flows (Friedrichs et al., 2016, Jenkins et al., 2007, Demir and Garcia, 2007). Object mobility in these cases is analyzed until coming to rest at an equilibrium state of burial. Less data exist for object response when subject to breaking waves and bore propagation, where conditions are more variable. Some recent efforts undertaken in the surf and swash zones involve deploying ‘smart’ surrogates encasing internal sensors to monitor object burial and migration (Calantoni, 2014; Bruder et al., 2017; Traykovski and Austin, 2017; Cristaudo and Puleo, 2019). Sensors include inertial motion units to detect both initiation of object motion and object displacement, and photocells to detect object burial and excavation rates. Surrogates in these cases are tested under very specific design scenarios in terms of wave magnitude, wave period and beach slope.

UnMES is designed around the existing knowledge obtained from the tests previously mentioned. Parameters such as munition density and shape have been identified as primary factors for determining whether a given munition will mobilize or remain at rest in a given environment. UnMES improvement requires the expansion of data-based models for mobility, burial and re-exposure (Rennie et al., 2015). The current model includes compiled laboratory and field data from a multitude of objects including cylinders, tapered cylinders and spheres of different densities and diameters. From these
results semi-empirical formulations have been constructed such as the Keulegan-Carpenter number ($KC$) and Object Shields parameter ($\theta$) and compared to object burial and depth ratios (Cataño-Lopera et al., 2011; Friedrichs et al., 2016; Rennie et al., 2017). $\theta$ is defined as

$$\theta = \frac{\tau_b}{(\rho_s-\rho_w)g d_{50}}$$

where $\rho_s$ and $\rho_w$ are the density of the sand and the density of water, $g$ is gravitational acceleration, and $d_{50}$ is the median sediment grain diameter. $\tau_b$ is the bed shear stress, defined as

$$\tau_b = \frac{1}{2} \rho_w f u^2$$

where $f$ is the friction coefficient equal to 0.03 (Puleo and Holland, 2001) and $u$ is defined as the characteristic fluid velocity. $\theta$ provides an indication on the initiation of object motion since it is proportional to the drag force divided by the submerged weight of an object. $KC$ is defined as

$$KC = \frac{u T_s}{D},$$

where $T_s$ is the wave period and $D$ is munition diameter. The $KC$ number provides an indication of the object displacement since it is a ratio of the drag forces to the inertial forces.

A visualization of compiled existing data for a state of equilibrium over time is provided in Figure 1.5 (Friedrichs et al., 2016). Plotting observations reveals the
existence of trends between these parameters and a final state of object burial-to-diameter \((B/D)\); Figure 1.4) ratios, as well as variability about this trend. A linear fit is applied to these data, determining coefficients for power law relationships. Empirical formulations are inserted into UnMES from which estimates on munition mobility can be made. Further results from new test scenarios allows for the development of new formulations and validation of coefficients embedded in the existing formulations mentioned.

![Figure 1.4: Sketch of example testing scenario defining burial \((B)\) and depth \((D)\) for a given surrogate.](image)
\[ \theta = \frac{\tau_b}{(\rho_s - \rho_w) gd_{50}} \]

\[ KC = \frac{u T_s}{D} \]

Figure 1.5: Compiled observations of \( B/D \) versus Object Shields parameter (\( \theta \)) and Keulegan Carpenter number (\( KC \)) currently incorporated in UnMES (Friedrichs et al., 2016).
1.3 Swash Zone Dynamics

The swash zone is the portion of the beach face that is intermittently subjected to both incoming bores (as a result of collapsed waves) that impinge the beach where they become swash, then return seaward as flow down an incline (Figure 1.5). The physical processes in this portion of the foreshore are difficult to measure due to instrumentation submergence/emergence and rapid morphodynamic changes. Field study instrumentation needs to be monitored and adjusted to maintain proper positioning. Laboratory studies allow for more control of desired hydrodynamic and morphodynamic conditions, but still contain inherent perturbations from many uncontrollable conditions. Hydrodynamics on a natural beach in the swash zone also have a high temporal and spatial variability (Chardón-Maldonado et al., 2016), since water depth and velocity evolve throughout a swash cycle and with tidal cycles.

Time series of water depth at a particular cross-shore location are asymmetric, increasing rapidly with uprush, and decreasing at a slower rate after flow reversal. This asymmetry is due to the influx of momentum of additional fluid into the back of the bore, as the bore front itself propagates landward, hindered by friction (Baldock et al., 2014). The acuteness of this asymmetry is dependent on both beach slope and location in the cross-shore, with a more symmetric response present on a gently sloped beach, and at a position more landward in the cross-shore (Guard and Baldock 2006). Water depth and maximum runup depend on offshore wave conditions, specifically wave amplitude, wave frequency and directional spreading. The most extreme conditions are associated with storm activity, where runup can reach higher portions of the foreshore not typically submerged. In consequence, this can lead to the excursion of objects thought to be stationary under normal wave conditions.
Velocities in the swash zone are also asymmetric. After a bore collapses, velocity during the uprush phase decreases due to the concurrent forces of gravity, pressure gradient and friction acting in the opposite direction (seaward) of propagation. Upon flow reversal, however, gravity and pressure gradient remain seaward directed, thus accelerating the flow (Baldock and Hughes, 2006). Typical maximum uprush velocities on natural steep beaches range from 1.5 to 3.0 m s\(^{-1}\) (Chardón-Maldonado et al., 2016). Maximum backwash velocities (observed from the same researchers) are generally slightly less than uprush values, ranging from 1.0 to 2.2 m s\(^{-1}\), which continues to accelerate from reversal until the next bore arrives. The specific velocity of each swash event depends on the transformation of each incident wave as it propagates through the surf zone, breaks, and enters the foreshore (Figure 1.5) and underlying infragravity motions.

The quantification of water depth and velocity are critical in determining typical coastal engineering parameters such as bed shear stress and sediment suspension. Asymmetric swash has been shown to exhibit significant net cross-shore elevation change, either resulting in large accretion or erosion events (Puleo et al., 2014b, Figure 1.6). In terms of munition mobility, it is crucial to monitor the hydrodynamics at various locations on the beach face since the variability previously discussed alters the corresponding forcing on objects. The scour from objects resting on a sandy beach as well as the sediment transport induced from swash both serve as mechanisms to either promote or impede the initiation of object mobility.
Figure 1.6: Schematic of the various zones along the cross-shore of a natural beach (adapted from Chardón-Maldonado et al., 2016).

Figure 1.7: Schematic of swash velocity and water depth and associated sediment transport (adapted from Masselink and Puleo, 2006).
1.4 Outline

The probabilistic nature of munitions response can be quantified during constant wave forcing in a laboratory setting. This paper focuses on the setup, analysis, results and further discussion of a laboratory experiment designed to develop techniques for tracking and predicting munitions motion. The results from this study can ultimately be incorporated into UnMES for determining munitions behavior and also serve as a benchmark for further laboratory studies under similar conditions. Future work will also be discussed.
Chapter 2

EXPERIMENTAL DESCRIPTION

2.1 Dam-break Swash

A dam-break wave maker has the capability of producing a ‘free’ swash event, meaning little interaction between a solitary bore and any subsequent wave motions. A dam gate holds back a reservoir of water (Figure 2.1), where upon initiation of a trigger rapidly releases the contained water and creates near-prototype swash (of that observed in a field setting). The swash motion then propagates across either a fixed or mobile bed at a desired slope and after reaching maximum runup reverses direction. A bore then returns to the reservoir and reflects of the back wall. A secondary gate is often used to resist this reflected wave, allowing only the original solitary wave to have an effect on the bed. Dam-break flumes have been used in laboratory experiments in the past to study sediment transport and swash zone dynamics due to this advantage (Kim et al., 2017; O’Donoghue et al., 2010; Steenhauer et al., 2011; Kikkert et al., 2012). A dam-break mechanism was designed with this knowledge at the Center for Applied Coastal Research (CACR) at the University of Delaware.

Figure 2.1: Diagram of dam-break flume.
2.2 Experimental Setup

A laboratory experiment was conducted in a wave flume (Figure 2.2) at the CACR to quantify the mobility of BLU-61 (Figure 2.3) surrogate munitions. The portion of the flume used in the study is 9.4 m long with a 1:7 sloping mobile bed \((d_{50} = 0.31 \text{ mm})\) established over the last 4.8 m. A dam-break mechanism was used to create a solitary swash event (Figure 2.4). A gate was resisted by vertical stops along the flume wall and retained a reservoir of water \((0.73 \times 1.00 \times 0.57 \text{ m}^3)\). The gate was raised rapidly by releasing a 45 kg mass on a 2.64 m rod hinged to a pinned support. The retained fluid was released and propagated down the flume as a broken bore. The bore impinged the sloping bed and collapsed as swash.

Water level was recorded at 10 cross-shore locations using resistance wave gauges (WG) recording at 16 Hz mounted on the flume wall and Banner ultrasonic distance meters (UDM) recording at 8 Hz mounted on carts along the flume wall (Figure 2.2). A Valeport electromagnetic current meter (EM) recording at 8 Hz was used to determine velocity at the toe of the beach and at the locations where surrogate munitions were deployed. The sensor is positioned roughly 0.02 m above the bed. The small elevation above the bed means that the entire swash event cannot be captured; a problem that occurs with any current meter in a swash zone study (Chardón-Maldonado et al., 2016). A wide-angle field of view camera (Prosilica GT1920, 3.5 mm lens) recording at 30 frames per second (fps) was deployed from overhead to capture the variations in sphere response based on the different initial conditions. A Velodyne Puck laser system with a motor of 600 RPM and data collecting at 10 Hz was mounted above flume and used to monitor bed variability and well as morphologic change after each swash event (see Section 2.4 for more description). A coordinate system (xyz) was implemented with the origin (0,0,0) set to the toe of the dam gate. Sensors were surveyed to flume
coordinates to provide correct representation of the hydrodynamic evolution from the reservoir to the point of maximum runup throughout testing. Time synchronization for the UDMs, WGs and EM was performed using a dedicated time server consisting of Tac32 and Dimension4 software and Garmin GPS module. The time server received respective Coordinate Universal Time (UTC) from accessible satellites and distributed this time to the computers logging sensor data.
Figure 2.2: Scaled model of flume set-up and testing positions for the spherical surrogates. Dimensions are in meters.
Figure 2.3: Single BLU61 cluster bomb (https://landmines.org.vn).

Figure 2.4: Snapshots of the dam-break mechanism upon initiation producing a swash event.
2.3 Testing Matrix

Munition size and density are two primary parameters believed to be important for mobility and burial (Rennie et al., 2017; Calantoni, 2017). For instance, objects with a specific gravity (SG) < 2 are thought to remain proud, while objects with a SG > 4 generally bury. Here, BLU-61 spherical surrogates of different SG but same dimensions (~ 0.08 m diameter) were constructed to quantify the importance of density to munitions response. Densities were altered using four different materials: concrete (SG = 1.8); aluminum (SG = 2.7); lead-core with a galvanized steel shell (SG = 4.2); and stainless steel (SG = 7.7). Note, the real BLU-61 has SG = 5.1. The four surrogate types were placed at five different cross-shore locations (Figure 2.2) on the sandy bed and were buried at three different initial burial depths (~ 0%, 30%, and 50% of total surface area) depending on the experimental run. Two surrogates could be tested concurrently afforded by adequate flume width for no interaction between them. Each scenario was repeated five times, producing 150 experimental tests. Experimental scaling of surrogate size and grain diameter is avoided due to swash velocities of roughly 2 m/s, similar to what is observed in the field (Masselink and Puleo, 2006). A surrogate was also constructed with fins similar to that of the BLU-61 munition and with a SG = 4.5. It was tested four times in the flume at Position 1 and burial ~ 0%.

2.4 Experimental Work-flow and Validation

Experiments were conducted during June, July and August of 2018. Conditions were controlled to a repeatable standard based on the limited time and funds available for a two-year project. Control of the initial morphology was necessary to reduce experimental perturbations and to capture the probabilistic nature of surrogate response under repeated hydrodynamic forcing. A wave was launched in the flume before each session to ‘wet’ the sediment in the flume, so each subsequent run had the initial
condition of a wetted beach face (from the run before). The beach was reset manually through the use of a heavy slider weight that was pulled across a metal track to smooth the beach face and maintain a 1:7 slope before each run (Figure 2.5). The Velodyne was used to monitor bed surface repeatability by calculating a root-mean-square error (RMSE) in elevation of a smoothed bed compared to an ideal profile. The system has 16 separate lasers and was mounted in such a way to have multiple transects scanning the smoothed profile. The raw data from the Velodyne was imported into Matlab, converted to flume coordinates and averaged across transects (Figure 2.7). A RMSE of < 3 mm relative to the baseline slope of 1:7 was maintained for each run. The UDM mounted above the reservoir (Figure 2.2) was used to verify the initial water depth remained between +/− 2 mm of the 0.73 m target depth.

\[
RMSE = \sqrt{\sum (z_{ideal} - z_{test})^2}.
\]
Figure 2.5: Snapshot of wave flume showing acceptable beach profile before bore launch.
Figure 2.6: (a) Raw laser scan of beach showing four transects. (b) Processed and averaged scan of current beach profile versus reference beach profile; in this example a RMSE = 1.8mm was recorded.
Chapter 3
ANALYSIS

3.1 Hydrodynamic Conditions

Parameterization of the hydrodynamic forcing is crucial in determining thresholds for surrogate mobility (e.g. object mobility number for dimensional analysis; Rennie et al., 2017). Quantities such as object acceleration, drag, reduced gravity and bottom friction all depend on the surrogate submerged volume upon impact. Thus, free surface and velocity data at the instant of mobilization must be measured directly or interpolated to a given location from available data (Figure 2.2). Ensemble averaging techniques were used to quantify variability in the experiment and determine a representative swash event. This type of averaging is useful in classifying the hydrodynamics at different positions in the cross-shore throughout time.

3.1.1 Water Depth

Water depth from WGs was determined through a calibration from voltage to measured water datum. Water depth from UDMs was calculated by subtracting detected distances from the surveyed sensor height. Data obtained from two WGs (Figure 3.1A, B) and three UDMs (Figure 3.1C-E) show the mean bore propagation of 10 runs (red) down the flume. The data also reflect the repeatability of the generated swash with a standard deviation (grey shading) of only +/- 2 mm for most of the event. Other water depth data not shown here exhibit similar repeatability. A reflected wave is only visible in Figure 3.1A-C, starting around 4 s for UDM1. A spatial snapshot of depth at a time of 3.1s (the vertical blue line in Figure 3.1A-E) is used to determine water depth throughout the
flume (Figure 3.1F). UDMs were not deployed above the beach slope to not obstruct the field of view of the overhead camera. Therefore, free surface was measured without surrogates in the flume and interpolated for the time of impact at the deployed location of the surrogate.
Figure 3.1: Determination of free surface from various sensors in the cross-shore. Linear interpolation between collected data allows for estimation of water depths at all locations.
3.1.2 Velocity

Velocity measurements from the EM were recorded five times at each position (Figure 2.2) and averaged to obtain an ensemble-averaged velocity time series (Figure 3.2). A second-degree polynomial fit was applied at each location assuming the dominant forces are friction and gravity (see Section 1.3). All fits resulted in a squared correlation coefficient ($R^2$) greater than 0.99, and a RMSE < 0.06 m/s. A UDM was deployed alongside the EM, to determine when water was present. Velocity was then extrapolated to this instant, ~0.4 s before the EM sensor head was submerged.

Initial velocities at all positions approached ~1.5 m/s, whereas different velocities were reached per position during backwash. Maximum backwash velocity is dependent on the amount of water accumulated landward of each position before flow reversal. Offshore positions were subject to a longer flow duration, allowing gravity to have a longer influence. Offshore-directed flows at Positions 1 – 3 approached velocity magnitudes equal to or greater than those upon impact.
Rectification and Camera Imagery

The imagery from the overhead camera were transformed from pixel coordinates (UV; Figure 3.3) into real-world coordinates (xyz; Figure 3.4). This technique, known as georectification, applies a non-linear regression algorithm to rectify an image based on internal camera parameters and geometric relations of image to ground coordinates (Holland et al., 1997). The lens calibration was performed using the Camera Calibration Toolbox for Matlab from the California Institute of Technology (CalTech), to correct for the ‘fish eye’ distortion. Calculated parameters from the calibration include the lens focal point, principal point, skewness, distortion coefficients and a pixel error. Black marbles placed on the beach slope as well as bolts located on the flume frame were surveyed and

Figure 3.2: Ensemble-averaged velocity data (symbols) and 2nd order polynomial fits (solid curve) at five cross-shore positions (identified in Figure 2.2).
used as ground control points (GCPs) in the rectification process. Images were rectified to the target beach slope in the flume. Note that parabolic distortions in Figure 3.3 become straight lines in Figure 3.4, except for pixels at the onshore and offshore regions due to the wide-angle lens and the flat (offshore) and shallower sloping (onshore) sections of the profile.

Figure 3.3: Raw, distorted overhead view of flume.
3.3 Object Tracking

Cross-shore position of each sphere was first identified by implementing a motion-based object tracking technique. Manual selection of spheres on rectified images was also performed in cases where the automatic tracking failed due to poor visibility (Figure 3.8). The series of steps for motion-based tracking are as follows.

The spheres were painted green (Figure 3.7) to easily identify them in each frame recorded by the overhead camera (Figure 3.5). The tracking entails applying a mask to each frame, which excludes all pixels not within the flume (Figure 3.7D, E) as well as all pixels that do not meet a certain intensity threshold (Figure 3.7C). In this case, the ‘green-most’ pixels were selected, since the spherical surrogates were painted a contrasting color to that of the background. Each raw image (Figure 3.6A) was first split into red-green-blue pixels (Figure 3.6B), and after choosing the most intense green pixels, a morphological enhancement was performed to select the two largest clusters of pixels. The clusters were enhanced to be the only identifiable features in the image (Figure 3.4: Rectified image to the target beach slope in the flume.)
3.6F). This series of modifications was applied throughout time to track the sphere trajectory. A cost assignment was applied after every detection to maintain the spheres as separate objects (Figure 3.7A). The spheres were not identifiable in every frame, especially when first impacted by swash and when they were transported during backwash to the highly turbulent region at the toe of the beach (Figure 3.8). A Kalman filter was applied to predict the new location based on past detections (Figure 3.7B). The Computer Vision Toolbox in Matlab was used to apply these corrections and maintain a constant time series of sphere detections. A visualization of the auto-tracking accuracy can be seen in Figure 3.8. The algorithm fails upon bore impact (~2 s) and at offshore locations less than ~10.5 m. Time series smoothing and input of manually identified surrogate locations were used to supplement the time series. Final surrogate locations were recorded after each test and used as the final position in the trajectory time series.

Figure 3.5: Image showing the camera used above the flume.
Figure 3.6: Series of image alterations used to identify only the two green spherical surrogates.
Figure 3.7: Detection of the spherical surrogates with mask alone (A) and with the assistance of a Kalman filter (B).
Figure 3.8: Trajectory comparison of auto-tracking method (yellow ‘x’) to manually identifying surrogate in each frame (blue line).
Chapter 4

RESULTS

4.1 Surrogate Response

Important parameters to extract from the observed sphere response include: initiation of motion, duration of mobility, maximum runup and run-down, maximum onshore- and offshore-directed velocities, initial burial depth and final burial depth. Sphere trajectories can be visualized using different image processing techniques. One technique is known as a time stack (Aagaard and Holm, 1989) that is used to compare sphere trajectories with wave runup. Time stack construction entails plotting a georeferenced transect of pixels on the y-axis over the entire swash duration (Figure 4.1). Plotting pixels in this manner allows for a depiction of the incoming bore and subsequent backwash (Figure 4.1, solid purple line). Plotting the response of five repeated runs highlights both the variability in response due to perturbations in the experiment (see Section 5.1) and the different trajectory characteristics due to density differences, with the lightest colors corresponding to the lightest spheres.
Figure 4.1: Sphere trajectories overlain on a runup time stack.
4.1.1 Averaged Responses

A reliable prediction for mobility can be made by averaging the trajectories of the 5 repeated runs. Averaged trajectories (Figure 4.2) were compared for different initial conditions and thresholds of motion for density, burial and position. Surrogate responses tested at position 2 for all burial depths are discussed here. Less dense spheres (Figure 4.2A, B) tend to mobilize upon initial impact, if not buried to 50% for the case of concrete and 30% for the aluminum sphere. For the denser spheres (Figure 4.2C, D) initiation of motion does not occur until late in the backwash for all burial depths. The lead-core sphere (SG = 4.2) then travels farther down slope since it is less resistant to the driving force of the backwash than the stainless steel sphere. The less dense spheres seem to extract similar momentum when placed proud, however, since they come to rest at similar offshore positions.

Offshore sphere motion occurs slightly before the runup edge reverses motion for cases when a sphere is mobilized on initial impact. This lead is due to the fact that local flow reversal occurs earlier than the leading swash edge reversal (Chardón-Maldonado et al., 2016). It is thus important to extract the local water velocity and depth to compare with the sphere velocity and initiation of motion. The associated water depth and velocity were extracted from the data record using the identified time of sphere mobilization. These values are then used in the parametrization of an object mobility number.
Figure 4.2: Sphere trajectories at the same cross-shore position at various initial burial depths.
4.1.2 Parameterization

Previous dimensionless parameters such as the Keulegan-Carpenter number ($KC$) and Object Shields parameter ($\theta$) were formulated by combining specific physical characteristics from the flow field (i.e. velocity, depth, density and period) and from the surrogates and sediment (i.e. density and diameter). $KC$ and $\theta$ were then typically compared to $B/D$ after a period of time where no significant burial or migration occurs and considered at a state of equilibrium (Friedrichs et al., 2016). The current experiment instead was conducted to determine the effect of a single swash event, thus total distance traveled ($D_t$) was considered as the object response. $D_t$ is defined as the addition of object uprush (landward) and backwash (seaward) motion. An approach similar to the formation of $\theta$ was chosen since this provides an indication of object mobility. The fluid drag (numerator) was adjusted since only a fraction of the surrogate may be exposed to the swash (water depth shallower than exposed portion of the surrogate). An Object Mobility number ($\theta_m$) was identified as

$$\theta_m = \begin{cases} 
\frac{\rho_w U^2 h}{g D (\rho_{obj} - \rho_w)} & h < (D - B) \\
\frac{\rho_w U^2}{g D (\rho_{obj} - \rho_w)} & h \geq (D - B)
\end{cases}$$

where $h$ and $U$ are water depth and velocity at the time of surrogate mobilization. $\rho_{obj}$ and $\rho_w$ are the density of the surrogate and the water. The denominator represents the object submerged weight. When $h$ exceeds $D - B$, the ratio is set to 1, meaning the surrogate is completely submerged. Results of $\theta_m$ are compiled for all $B/D$ scenarios and positions (Figure 4.3). Each point represents an averaged $D_t$ for the five repeated runs. A $R^2$ was calculated and equals 0.7. Note that the stainless steel sphere (SG = 7.7) did not exhibit
enough movement instantaneously under the tested flow conditions, thus data are restricted to the y-axis. The BLU-61 surrogate constructed with fins exhibited behavior similar to that of the Lead Core surrogate tested at the same position and burial depth.

Figure 4.3: Observations of total distance traveled ($D_t$) as a function of Object Mobility number ($\theta_m$). Triangles denote results with $B/D = 0.1$, circles with $B/D = 0.2$, and squares with $B/D = 0.5$. 

![Averaged Results (All Burials & Positions)](image-url)
5.1 Force Balance

Evaluation of the forces present under fluid flow can lead to a better understanding of surrogate response for given conditions. Table 5.1 provides formulations of the forcing mechanisms thought to exist for bore impact on a solid body and thus cause surrogate mobility (Cristauo and Puleo, 2019). Stabilizing forces such as weight and suction tend to preserve the surrogate’s position. The construction of a force balance with an input of experimental results could further enlighten a true threshold for surrogate mobility. The variables involved in the formulation of the forcing terms reflect characteristics of the flow, surrogate properties, surrogate position and known empirical coefficients (Figure 5.1). A force balance for the surrogate would require input of the flow characteristics as the surrogate itself migrates across the beach face. Other processes such as scour, sediment transport and turbulence complicate the construction of a force balance that could be used for surrogate mobility.
Table 5.1: Terms for surrogate force balance.

<table>
<thead>
<tr>
<th>Term</th>
<th>Equation</th>
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<tbody>
<tr>
<td>Surge Force</td>
<td>( F_s = \rho_w A_p u^2 )</td>
</tr>
<tr>
<td>Object Acceleration</td>
<td>( F_m = (\rho_{obj} + \rho_w C_m)V_{obj} \frac{dU}{dt} )</td>
</tr>
<tr>
<td>Fluid Acceleration</td>
<td>( F_w = (1 + C_m)\rho_w V_{obj} \frac{du}{dt} )</td>
</tr>
<tr>
<td>Drag Force</td>
<td>( F_D = \frac{1}{2} C_d \rho_w \frac{A_p}{A} u</td>
</tr>
<tr>
<td>Lift Force</td>
<td>( F_L = \frac{1}{2} C_L \rho_w \frac{A_p}{A} u</td>
</tr>
<tr>
<td>Reduced Gravity</td>
<td>( F_r = (\rho_{obj} V_s - \rho_w V_{obj}) g \sin \beta )</td>
</tr>
<tr>
<td>Friction</td>
<td>( F_f = C_f (\rho_{obj} - \rho_w) V_{obj} g \cos \beta )</td>
</tr>
</tbody>
</table>

\( \rho_w = \text{density of water} \)  \( U = \text{object velocity} \)
\( \rho_{obj} = \text{density of object} \)  \( C_m = \text{added mass coef.} = 0.5 \)
\( V_{obj} = \text{volume of object} \)  \( C_f = \text{drag coef.} = 0.5 \)
\( V_s = \text{submerged volume} \)  \( C_f = \text{lift coef.} = 0.5 \)
\( A = \text{total projected area} \)  \( C_f = \text{friction coef.} = 0.45 \)
\( A_p = \text{submerged projected area} \)  \( g = \text{gravity} \)
\( u = \text{fluid velocity} \)  \( \beta = \text{beach slope} \)

Figure 5.1: Sketch of variables used to define forcing terms.
5.2 Variability

Experimental repeatability is dependent on selecting thresholds to maintain for controllable variables such as water depth, choosing the control variables themselves, and uncontrollable inherent instabilities of turbulent flows (Pope, 2000). Initial reservoir volume and beach morphology were the main control variables in the present experiment. Each experimental scenario was repeated to capture the variability in object response due to the limitations mentioned.

5.2.1 Surrogate Response

Trajectories of five repeated runs were averaged and used to measure surrogate mobility to provide quantification of the mean response. Averaged trajectories (red lines in Figure 5.2) were constructed by averaging the tracked positions of the surrogate for each run (Figure 4.1). Timing of initiation of motion was specifically important since this point in time was used to extract a water depth and velocity sufficient to initiate mobility. For example, the maximum runup position of the concrete sphere tested at position two and depth three (50%) varied by ~ 0.8 m (width of orange fill in Figure 5.2). The final position, however, was observed to be the same (~ 11.4 m) for all five runs. The aluminum sphere for the same scenario also exhibited variability in the time of initiation. Mobility began upon impact (~ 3.0 s) for several cases, but initiated upon backwash (~ 6.2 s) for others (Figure 5.2).
5.2.2 Additional Variability

Sediment saturation and compaction were two conditions not controlled in the present experiment. Saturation was measured throughout testing using ECH20 moisture sensors at five different cross-shore locations (Figure 5.3). Moisture content increased after each run per day (Figure 5.4) and throughout the week (testing Monday through Friday, typically). A preliminary wave was launched at the start of each day before testing to wet the surface of the beach. This, however, was not sufficient to
reach a repeatable level of saturation. Wave 1 in Figure 5.4 was the first experimental wave launched after the preliminary wave. Waves 2-4 then experienced ~ 10% increase in saturation, suggesting a second preliminary wave would make the moisture content more reproducible. The compaction of sediment around spheres was also not monitored. After the beach was scanned, a section of sand was removed to create an impression corresponding to the desired depth to diameter ratio. A caliper was used to measure the impressions before the surrogates were placed. It is unknown how these conditions may have contributed to the variability in surrogate response.

Figure 5.3: Sketch of the EC moisture sensor locations under the beach face.
Figure 5.4: Variability in moisture content over four consecutive waves.
Chapter 6

CONCLUSIONS

A laboratory experiment in a dam-break wave flume was performed to investigate surrogate response under repeatable forcing. Surrogates were constructed to resemble the same shape as the BLU61 cluster bomb, but span a range of densities. Surrogates were also placed at five different cross-shore positions and at three different burial depths on a sandy bed. The wave flume produced a single swash event that propagated along the flume and impacted the surrogates, often initiating motion. Imagery of the flume was captured by an overhead camera and rectified to real world coordinates. The trajectories of the surrogates were traced using a motion-based tracking technique and manually corrected when visibility was poor.

Surrogate trajectories were averaged to analyze the mean response due to variability inherent in both turbulent flows and in choosing and maintaining experimental control variables. Initiation of motion was calculated and used to extract local water depth and velocity at the instant of mobilization. These parameters, as well as other characteristics of the flow field and physical surrogate properties, were combined to identify an Object Mobility Number ($\theta_m$). Total distance traveled ($D_t$), defined as the sum of uprush and backwash, was chosen to quantify surrogate response. Travel distance was moderately correlated to $\theta_m$ (squared correlation coefficient of 0.65) when combining all relative burial ratios ($B/D$) ratios and initial cross-shore positions. Surrogates with lower specific gravities experienced higher $\theta_m$. Less dense surrogates also initiated sooner than denser surrogates, when velocity is at
a maximum, resulting in higher $\theta_m$. These results are expected due to the construction of $\theta_m$, where a smaller density decreases the denominator and a larger velocity increases the numerator. The stainless steel surrogate had a large enough density to restrict instantaneous motion under the present forcing, though an offshore displacement of \(~0.4\ m\) was observed during backwash. No net onshore motion was recorded for all tested scenarios. Surrogates either initiated upon impact and underwent reversal past the point of initial placement or initiated during the backwash phase of flow.

The results of this experiment reveal specific munition behavior in the swash zone, where hydrodynamics are difficult to quantify and minimal data exist. The surrogates tested were limited to resemble spherical munitions. Munitions shaped as cylinders, as conical frusta or with other more complex geometries require additional laboratory testing. The current results can be incorporated into predictive models such as the Underwater Munitions Expert System (UnMES) to forecast munition mobility and migration based on flow field conditions and munition classification. Advancements in the predictive outputs from UnMES allow personnel at contaminated sites to more efficiently manage munition distribution.
REFERENCES


